

COMPLEX LEARNING AND INFORMATION PROCESSING BY PIGEONS: A CRITICAL ANALYSIS

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Three models of conditional discrimination learning by pigeons are described: stimulus configuration learning, the multiple-rule model, and concept learning. A review of the literature reveals that true concept learning is not characteristic of the behavior of pigeons in matching-to-sample, oddity-from-sample, or symbolic matching studies. Instead, pigeons learn a set of sample-specific S^D rules. Transfer of the discrimination to novel stimuli, at least along the hue dimension, is predicted by a "coding hypothesis", which holds that pigeons make a unique, but usually unobserved response, R_1 , to each sample, and that the comparison stimulus chosen depends on which R_1 was emitted in the presence of the sample. Convincing evidence is found that pigeons do code sample hues, but there is little evidence that allows one to infer that the "coding event" must have behavioral properties. Parameters of the conditional discrimination paradigm are identified, and it is shown that by appropriate parametric manipulation, a variety of analogous tasks may be generated for both human and animal subjects. The tasks make possible the comparative study of complex learning, attention, memory, and information processing, with the added advantage that behavior processes may be compared systematically across tasks.

Key words: conditional discrimination, matching-to-sample, oddity-from-sample, symbolic matching, coding hypothesis, information processing, short-term memory, attention, rule learning, concept learning, stimulus configuration learning, pigeon

CONTENTS

Three Models of Conditional Discrimination Learning	
The configuration model	
The multiple-rule model	
The single-rule model	
Cumming and Berryman's Matching-to-Sample Procedure	
Some Important Special Cases of the Paradigm	
Delayed matching and short-term memory	
Information retrieval	
Vigilance and the maintenance of attention	
Stimulus complexity and attention	
Number of stimuli	

Scope of the Review

Conditional Discrimination Learning by Pigeons	
The Coding Hypothesis	
Effects of Intermittent Schedules	
Studies of Symbolic Matching	
Studies of Short-Term Memory	
The Problem of Attention	
Single-Rule (Concept) Learning	
Conclusions	
References	

An appropriate paradigm is essential to studying the interrelations among several processes including complex learning, memory, information processing, and perception. In our view, the conditional discrimination paradigm is best suited for the task. The literature contains hundreds of conditional discrimination experiments. However, only a small number of papers have addressed the problem of developing a broad conceptual framework useful for the comparative study of behavior processes. As we attempt to meet this challenge, we will examine the literature and assess the extent to which the paradigm may be used to meet our goal. With few ex-

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ceptions, our review is limited to work done with a single species: the pigeon.

Three Models of Conditional Discrimination Learning

In a now classic paper, Lashley (1938b) described a series of experiments in which he established conditional reactions in three rats. In a simple discrimination problem, one of a pair of discriminative stimuli is always correct. However, in the conditional reaction, or conditional discrimination problem as it is currently called, a second cue or sign is required to indicate which of the discriminative stimuli is correct on any given trial. Although the subject is never required to respond directly to the sign, the sign does appear to exert a kind of stimulus control over the subject's behavior, such that it determines which of the discriminative stimuli will be chosen.

In Lashley's experiment, the discriminative stimuli were always a pair of equilateral triangles, one upright and the other inverted. A standard jumping stand (Lashley, 1930) was used. Both triangles appeared on every trial. Although the background (or sign) on which the triangles appeared was always the same on any given trial, it was varied each time the rats met the learning criterion of 20 successive errorless trials. When the background was black, jumping toward the upright triangle was reinforced.² However, if the background consisted of horizontal stripes, the rats were required to choose the inverted triangle.

When Lashley's data are examined both in terms of the number of trials required to meet the discrimination criterion and the number of errors made during those trials, all rats showed a marked improvement by the end of the experiment. In many instances, reversing the background produced an immediate change (*i.e.*, without any errors at all) in the choice of the new positive stimulus over the old one. It appears that Lashley had, indeed, established a kind of stimulus control over his subjects, such that the direction or sense of the reaction was conditional on an additional stimulus in

the experimental situation. Later, Lashley demonstrated that the background could be randomly alternated from trial to trial without disrupting the discrimination.

Lashley was not the first to study conditional discriminations. In fact, there is an anecdotal report of the use of such problems dating back as far as 1799 (Itard, 1932; Lane, 1976). And both American and Russian investigators were early to recognize the usefulness of the conditional discrimination paradigm for studying the conceptual behavior of nonhuman primates (Revesz, 1925; Robinson, 1933; Yerkes, 1935; Yerkes and Petrunkevitch, 1925). What made Lashley's paper so important is that he was the first to define the issues as those of identifying the physical properties of the controlling stimuli and of specifying the extent to which that control can be transferred to novel stimuli. Lashley's discussion foreshadows the emergence of three models for conceptualizing the nature of conditional discrimination learning. None of the models logically requires the use of intervening variables, although their use is not uncommon.

The configuration model. In Lashley's experiment, the physical nature of the stimuli is complex, but the simplest model holds that all aspects of the stimulus situation, or configuration, that can be detected by the subject come to exert some control over the discriminative response. Lashley's stimulus cards are shown in Figure 1, and to each of these four configurations a specific response is conditioned. Although the experimenter records only two responses (upright triangle chosen or inverted triangle chosen) it is implied that each response is learned separately to two configurations. Examples of theorists who have found the configuration model useful in the analysis of discrimination learning are Gulliksen and Wolffe (1938) and Spence (1952). Lashley rejected the configuration model after finding some instances of positive transfer to new cards containing variations of the figure, of the background, or both.

The multiple-rule model. We may refer to the discriminative stimuli from which the subject must choose as figure, and all other detectable aspects of the configuration as ground. The multiple-rule model holds that some specific aspect (or sign) within the ground comes to control each choice. At the descriptive level we may say that the subject has learned a set

²Studies of conditional discrimination need not be limited to the instrumental conditioning paradigm. For example, see Asratyan (1961), Saavedra (1975), and Looney, Cohen, Brady, and Cohen (1977). The paper by Looney *et al.* is particularly interesting to us because it discusses some of the work described in our manuscript.

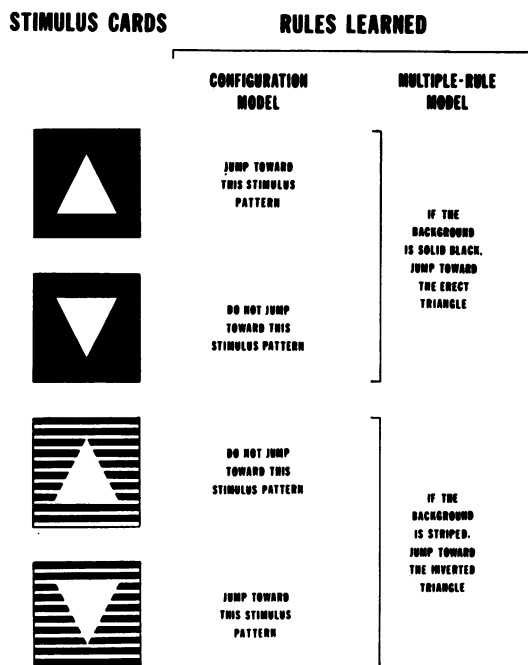


Fig. 1. The stimulus cards used by Lashley (1938b) in his study of conditional discrimination learning by rats. The rules assumed to be learned by both the configuration model and the multiple-rule model are compared.

of "if . . . , then . . ." rules (Carter, 1971; Carter and Eckerman, 1975). It should not be inferred from this statement that the term "rule" must assume the status of a theoretical variable. Although rule learning is frequently an important part of cognitive learning theories (e.g., Harlow, 1959; Levine, 1975), we refer here only to the empirically demonstrable relationship between the presentation of a critical feature of the ground (the sign) and the selection of a particular discriminative stimulus. There is a different sign for each of the discriminative stimuli (leading some investigators to apply the term "multiple-sign learning" to the solution of this type of problem), but only one sign is presented on any given trial. Within the context of Lashley's study, the rules from the point of view of the experimenter are (1) "if the background is black, then choose the upright triangle" and (2) "if the background is striped, then choose the inverted triangle". The actual features of the background that are critical in controlling the selection of triangles must be identified empirically. The multiple-rule model, as described above, implies nothing about the ex-

tent to which a response will transfer to a novel sign.

Two varieties of rule may be distinguished: (1) those that specify which choice is correct and (2) those that specify the wrong choice (Cumming, Berryman, and Cohen, 1965). One distinguishes between these two alternatives on the basis of the extent to which novel choices, rather than novel signs, disrupt a well-established conditional discrimination.

Sometimes an additional feature is added to the multiple-rule model, thus allowing certain predictions concerning transfer obtained with novel signs. In order to make these predictions it is assumed that any novel sign will be treated by the subject as if it were one of the original signs to which the subject has already been trained. Sometimes called the *coding hypothesis*, many investigators have assumed that the presentation of a sign evokes either a covert response or some unspecified neural event, which in turn governs the choice of discriminative stimuli (Lawrence, 1963; Schoenfeld and Cumming, 1963). Coding assumes the status of a true intervening variable in most, if not all, instances.

The single-rule model. Following the procedures described above, Lashley continued training with a number of new stimulus cards, varying both figure and ground. He was trying to establish a "generalized reaction" such that the behavior of his rats could be described by a single rule: "any stimulus which is correct in the presence of sign A is incorrect in the presence of sign B". The rats failed this problem.

The most important feature of the single-rule model is that it specifies that the subject will continue to respond correctly in a new situation as long as each new discrimination problem fits the specifications of the rule. Both matching and oddity performances may be viewed as instances of behavior governed by a single rule, provided that it can be shown empirically that the subject continues to match or to choose the odd stimulus in accordance with previous training, even though the stimuli used are being presented for the first time.

In part because Lashley had failed to demonstrate single-rule learning, later investigators have emphasized the matching and oddity principles as the potential bases for solution of their conditional discrimination problems. For this reason, most of the studies reviewed below

use three or more stimuli on each trial. A description of the procedures employed by Cumming and Berryman (1961, 1965) will serve to illustrate the modifications required in the paradigm. We will specify systematically all of the important parameters that may be manipulated in the study of conditional discrimination learning. We will also show that many of the classical paradigms of interest to psychologists may be viewed as special cases of conditional discrimination. The advantage of examining these special cases within the context of a single paradigm is that the study of the interrelations among several important psychological processes may be greatly enhanced.

Cumming and Berryman's Matching-to-Sample Procedure

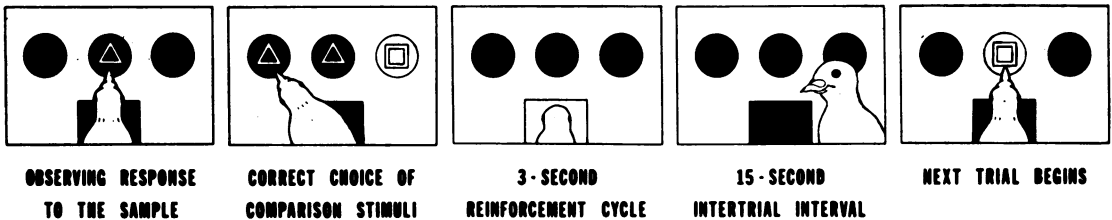
Cumming and Berryman's studies of matching behavior usually involved the use of hues.

However, we will describe the variations of the matching paradigm in terms of stimuli varying in two dimensions, geometric form and background hue. Extensions to other kinds of matching problems and to oddity are obvious.

Figure 2 shows a schematic representation of the *simultaneous matching* procedure. Between trials all keys are dark, although general illumination in the chamber is provided. At the beginning of a trial, the center key is transilluminated with a white triangle on a red background. (Red is represented by the darker of two shades in Figure 2.) The stimulus on the center key is called the *sample* or the standard stimulus. A single peck on the center key produces a different stimulus on each of the side keys, one of which always matches the sample. Stimuli on the side keys are called *comparison stimuli*. A response to the matching comparison stimulus is reinforced with food; a response to the nonmatching key produces a

MATCHING - TO - SAMPLE — NON-CORRECTION PROCEDURE

CORRECT SEQUENCE OF RESPONSES



INCORRECT SEQUENCE OF RESPONSES

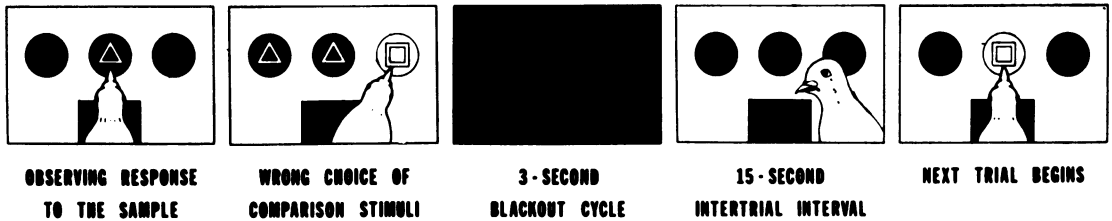


Fig. 2. A schematic representation of the simultaneous matching-to-sample procedure. The top row of panels shows what happens when the pigeon makes the correct choice of comparison stimuli. The consequences of an error are shown in the second row of panels. Two features of the procedure illustrated here were never used in Cumming and Berryman's laboratory. First, the stimuli vary both in geometric form and background hue. (The differential shading of the background is meant to represent two separate hues.) A correction procedure is illustrated in which a trial is repeated every time an error occurs. The use of a correction procedure in studies of matching-to-sample is not common.

short blackout (Ferster and Appel, 1961; J. Zimmerman and Ferster, 1963). As illustrated in Figure 2, the matching-to-sample technique includes a correction procedure in which a trial is repeated indefinitely if errors continue to occur. Birds advance to the next trial only following a reinforcement. Most investigators (e.g., Cumming and Berryman, 1961, 1965) have not used the correction procedure. It is illustrated here to facilitate the discussion of one of the experiments reviewed below.

In simultaneous matching, the center key remains lighted until the end of the trial, although variations in this procedure are in common use. For example, if a response on the center key turns off the sample and, at the same time, turns on the comparison stimuli, the procedure is called *zero-delay matching*. If a period of time elapses between offset of the sample and onset of the comparison stimuli, the procedure is called *delayed matching*. Delays may be of either fixed or variable duration.

The decision to reinforce responses to the comparison key that matches the physical properties of the sample is as arbitrary as the choice of temporal parameters. Two variations in procedure are of particular interest. We generate *oddy problems* by reinforcing responses to the nonmatching key, a procedure that is occasionally called by other names (e.g., *oddy-from-sample*, *mismatching*, and *non-matching*). In another variation of procedure, *symbolic matching*, the relation between the sample and the comparison stimuli is arbitrary. For example, with three hues, the reinforcement contingencies for symbolic matching might be: (1) if the sample is red, reinforcement is available for pecking blue, (2) if the sample is blue, responses to the green key are reinforced, and (3) if the sample is green, responses to red are correct. In symbolic matching there is no requirement that the stimuli be on the same continuum; hue samples could be "matched" to geometric forms on the side keys. The only restrictions on symbolic matching contingencies are (1) the sample and the correct comparison stimulus must not be physically identical and (2) there must be one, and only one, correct comparison for each sample. All of the temporal parameters that may be varied in matching-to-sample experiments may also be manipulated in studies of symbolic matching and symbolic oddity.³

One word of caution is necessary. In studies of symbolic matching, or amatching as it is sometimes called, we may not wish to think of the behavior observed as being necessarily symbolic. Later in this paper, we will treat the issue of establishing criteria that must be satisfied before behavior is called symbolic. For the moment, it is only necessary to think of "symbolic matching" as the name of a specific procedure.

Some Important Special Cases of the Paradigm

By the appropriate manipulation of certain parameters, matching-to-sample may be made analogous to several classical paradigms well known to experimental psychologists who specialize in the study of human behavior. A few of the most important examples are described below.

Delayed matching and short-term memory. A number of investigators have recently turned to variable-delay matching tasks in an attempt to find an animal analogue of the short-term memory procedure made popular by Peterson and Peterson (1959). After training with some form of matching-to-sample task, a delay interval is imposed between offset of the sample and onset of the comparison stimuli, and the length of the delay interval is varied from trial to trial. Jarrard and Moise (1971) speculated that animal memory experiments, particularly those using nonhuman primates as subjects, may prove to be the only possible sources of data free from the influence of rehearsal and uncontaminated by the use of materials of unknown familiarity to the subject. Both Jarrard and Moise (1971) and D'Amato (1973) have undertaken extensive research programs to explore such possibilities. For a more detailed discussion of the methodology of animal memory studies, see Winograd (1971), Honig and James (1971), and Medin, Roberts, and Davis (1976).

Information retrieval. If the temporal relations of the matching paradigm are reversed, another variation of memory experiment becomes possible. Suppose that the comparison

³The rules for symbolic hue oddity are "if the sample is red, peck red or green, whichever is available", "if the sample is green, peck green or blue, whichever is available", and "if the sample is blue, peck blue or red, whichever is available".

stimuli are exposed before the subject is allowed to see the sample. If a delay is interposed between the offset of the comparison stimuli and the onset of the sample, requiring the subject to respond to the dark key on which the correct stimulus was previously projected provides what may be a good analogue of Sperling's (1963) partial report procedure. The animal must remember the entire array of comparison stimuli until the sample stimulus appears and provides the subject with information concerning that part of the comparison array that is relevant on that particular trial.

Vigilance and the maintenance of attention. When human observers are asked to scan visual displays over long periods of time, the effort they expend looking for targets depends on the likelihood that a target will be seen and on the degree to which the subject can predict when the target will appear (Holland, 1958). Depending on the schedule of reinforcement employed, the rate of observing may be constant or it may exhibit a variety of temporal patterns similar to the changes in rate of responding by animals generated by comparable reinforcement schedules. Animal subjects may be particularly useful when we are concerned with changes in the rate and accuracy of observing behavior over very long periods of time or under particularly adverse conditions.

Stimulus complexity and attention. The stimuli selected for an experiment may differ in one dimension, as in the case of simple hue matching, or they may differ along several dimensions. If chosen and manipulated properly, complex stimuli make possible the study of selective attention. The procedure illustrated in Figure 2 involves stimuli varying both in geometric form and background hue. The problem can be solved on the basis of either form or hue alone. Thus, the procedure allows us to determine whether one of the stimulus dimensions is salient over the other when form and hue provide redundant information. Maki and his associates have also used complex samples to force pigeons to encode more than one stimulus property on each trial (Maki and Leuin, 1972; Maki and Leith, 1973; Maki, Riley, and Leith, 1976). For related treatments of attention, see Riley and Leith (1976), Heinemann and Chase (1970), Heinemann, Chase, and Mandell (1968),

Blough (1972), Boneau and Honig (1964), Yarczower (1971), Reynolds and Limpo (1969), and Nevin and Liebold (1966).

Number of stimuli. Related to the determination of the "information-processing capacity" of nonhuman organisms is the number of stimuli to be learned. The number of stimuli may determine either the number of configurations or the number of rules that the subject must learn. In most experiments, the number of samples is equal to the number of comparison stimuli. However, this need not be the case. For example, if the number of samples exceeds the number of comparison stimuli, the subject is forced to categorize the stimuli presented as samples. An outstanding example of the use of this method is found in a study by Wright and Cumming (1971) in which they were able to show that pigeons divide the spectrum into three invariant categories.

Scope of the Review

If the basic processes that underlie learning and performance are to be compared, behavior must be studied within a single paradigm. The conditional discrimination paradigm has sufficient flexibility to generate most of the special cases of interest to both learning theorists and cognitive psychologists, and the interactions among processes may be studied by appropriate parametric manipulations.

What follows is a selective review and analysis of conditional discrimination learning by pigeons. Pigeons, monkeys, and children have been studied extensively. We have limited our discussion to the behavior of a single species in an attempt to show how programmatic research in the learning laboratory may contribute most effectively to the solutions of some of the conceptual problems faced by contemporary theorists in several areas of psychological inquiry.

Conditional Discrimination Learning by Pigeons

We begin our review of the pigeon studies with the work of Cumming and Berryman and their students. In their first experiment (Cumming and Berryman, 1961), three pigeons were trained on a simultaneous matching-to-sample problem using three hues: red, green, and blue. Matching performance was poor for the first three or four sessions because each bird exhibited a strong position bias. However,

within six to nine sessions, all birds reached a level of at least 90% accuracy, after which they gradually improved until near-100% performances were a daily occurrence.

Another kind of bias also occurs early in training. Matching accuracy has been shown to be somewhat below chance on the first session (Carter, 1971). On the first few trials of Session 1, pigeons almost always peck the odd key. This initial oddity preference is not difficult to understand. Paraphrasing a suggestion by Berryman, Cumming, Cohen, and Johnson (1965, pp. 770-771), once matching behavior has been learned, responses to the sample stimuli are maintained by conditioned reinforcement provided by the onset of the comparison stimuli. However, before this chain is well established, birds frequently begin a trial by emitting several responses to the stimulus on the center key. These responses to the sample are effectively extinguished, and this may well decrease the probability that a bird will respond again to the same hue when it appears as one of the comparison stimuli.

Extinction of responses to the sample hue should also have an effect on the acquisition of oddity discriminations. Recent data have confirmed this expectation (Berryman *et al.*, 1965). Six pigeons were trained on a simultaneous oddity problem, again using red, green, and blue stimuli. The acquisition curves show that the subjects began at levels well above chance accuracy, but they improved only slowly. At no time did these birds exhibit position preferences as strong as pigeons in simultaneous matching experiments, and the elimination of the position habit does not appear to be correlated with the acquisition of oddity.

In oddity experiments, acquisition may be accounted for in either of two ways. Consider a trial on which the sample is red and the comparison stimuli are red and green. It could be assumed that the bird has learned to avoid S^A (red on the side key). In other words, the subject might learn the rule "after pecking red on the center key, avoid pecking red on the side keys". The sample is assumed to serve as a cue designating which of the comparison stimuli is S^A . Rules of this type will be called S^A rules.

But another interpretation is possible. The pigeons could have learned to approach S^D . Said in another way, the birds may have learned the rule "after pecking red on the

center key, approach and peck green on the side keys". This is an S^D rule.

In the original oddity procedure used by Berryman *et al.* (1965), it was not possible to determine whether their birds were following S^D or S^A rules. Therefore, they altered their procedure after the twentieth session by replacing all of the blue key lights with yellow ones. No other changes were made.

The S^D and S^A rules lead to different predictions about the way birds should transfer oddity behavior to novel stimuli. It will be helpful to use the following notation system: a trial designated as $R(R,G^*)$ signifies a trial with red on the center and red and green on the side keys. The first letter indicates the sample hue and the letters within the parentheses indicate the hues of the side keys, irrespective of position. The asterisk indicates the correct comparison hue.

The transfer predictions of interest concern the trials on which the novel stimulus appears only on a side key, *i.e.*, trials on which one of the following changes in stimuli has been made:

- (1) $G(G,B^*) \rightarrow G(G,Y^*)$
- (2) $R(R,B^*) \rightarrow R(R,Y^*)$.

On a transfer trial with a green sample, $G(G,Y^*)$, a bird that has learned a set of S^D rules would do no better than it did on the first session, because green on the center key is a cue for selecting either red or blue and neither is available. In contrast to this prediction, birds that have learned a set of S^A rules should show no change in performance because the birds would already have learned to avoid a green comparison after pecking a green sample. Similar predictions may be made for trials on which the sample is red.

The data from the transfer test have been averaged for all six birds and are presented in Table 1. Both for trials on which the sample was green and trials on which it was red, oddity performance dropped on the first day after yellow stimuli had been substituted for blue ones to a level very near that on the first day of training. These data suggest that oddity behavior is best described by a set of double S^D rules ("if red, peck blue or green, whichever is available"; "if green, peck red or blue"; and "if blue, peck red or green").

In Cumming and Berryman's (1961) original simultaneous matching experiment, an identi-

Table 1

Mean accuracy on the blue comparison trials for the first and last days on which blue appeared as an alternative and for yellow comparison trials on the first day on which the novel yellow stimulus was substituted for blue.

	Mean % Correct for Six Birds		
	Session 1 with Blue	Session 20 with Blue	Session 1 with Yellow
G(G,B*) → G(G,Y*)	71	91	70
R(R,B*) → R(R,Y*)	66	94	59

cal transfer test was given after the twenty-second training session. On trials on which yellow appeared only as a comparison stimulus, R(R*,Y) and G(G*,Y), matching accuracy remained high, indicating that matching-to-sample is also best described by a set of sample-specific S^D rules ("if red, peck red"; "if green, peck green"; and "if blue, peck blue"), half the number of S^D rules required to solve the oddity problem.

Prompted by the analysis presented above, Cumming and Berryman (1965) used data from their original experiments to compare acquisition functions for matching and oddity directly. The group data from both experiments have been plotted on the same set of axes in the lower portion of Figure 3. The figure clearly shows the very slow, almost linear acquisition curve for oddity, compared with relatively rapid acquisition of matching behavior, following approximately three sessions of near-chance performance.

It is also of interest to compare matching and oddity when only two hues are used. Zentall and Hogan (1974b) published appropriate data that are reproduced in the upper panel of Figure 3. The scale along the abscissa of the upper panel is different from that of the lower panel because of a difference in the lengths of experimental sessions. As the figure is presented, the scales are equal in terms of the number of trials, rather than the number of sessions. There appears to be no difference in the rate of learning of matching and oddity when only two hues are used.

The importance of the number of stimulus alternatives may be explained best by reference to Table 2. Table 2 presents the stimulus combinations (irrespective of position) used in matching, oddity, and symbolic matching ex-

Table 2

Stimulus combinations (without regard to position) used in matching, oddity, and symbolic matching procedures for different numbers of alternatives.

	Matching	Oddity	Symbolic Matching
Two Alternatives			
	R(R*,G) G(G*,R)	R(R,G*) G(G,R*)	R(R,G*) G(G,R*)
Three Alternatives			
	R(R*,G) R(R*,B) G(G*,R) G(G*,B) B(B*,R) B(B*,G)	R(R,G*) R(R,B*) G(G,R*) G(G,B*) B(B,R*) B(B,G*)	R(R,B*) R(G,B*) G(G,R*) G(B,R*) B(B,G*) B(R,G*)

periments for two and three stimulus alternatives. In oddity experiments, in which pigeons behave according to S^D rules, the bird must learn a total of six rules for three sample hues, but matching birds require only three S^D rules to solve the problem. Presumably, the greater the number of rules the birds must learn the greater the number of sessions required for acquisition.

The data shown in Figure 4 support this hypothesis. Cumming and Berryman's (1961) original matching data are compared directly to the acquisition function for oddity, but a simple multiplicative transformation has been made on the abscissa. Because matching birds (with three alternatives) need learn only half the number of S^D rules needed to master the oddity problem, they might be expected to learn twice as rapidly as the oddity group. For this reason, the scale of the lower abscissa (for matching) has been doubled. If matching is acquired twice as rapidly as oddity, both functions in Figure 4 should reach a point where they coincide during the final course of acquisition.

The matching data are shown by the unfilled triangles connected by dashed lines. At the beginning of the matching experiment, birds show approximately 50% accuracy. Although little change in behavior occurs until the fourth session, thereafter acquisition is rapid until the matching birds catch up with the oddity group. For the remainder of the experiment, the matching and oddity groups show highly similar performance. The oddity preference prevents the functions from coinciding only during the earlier sessions.

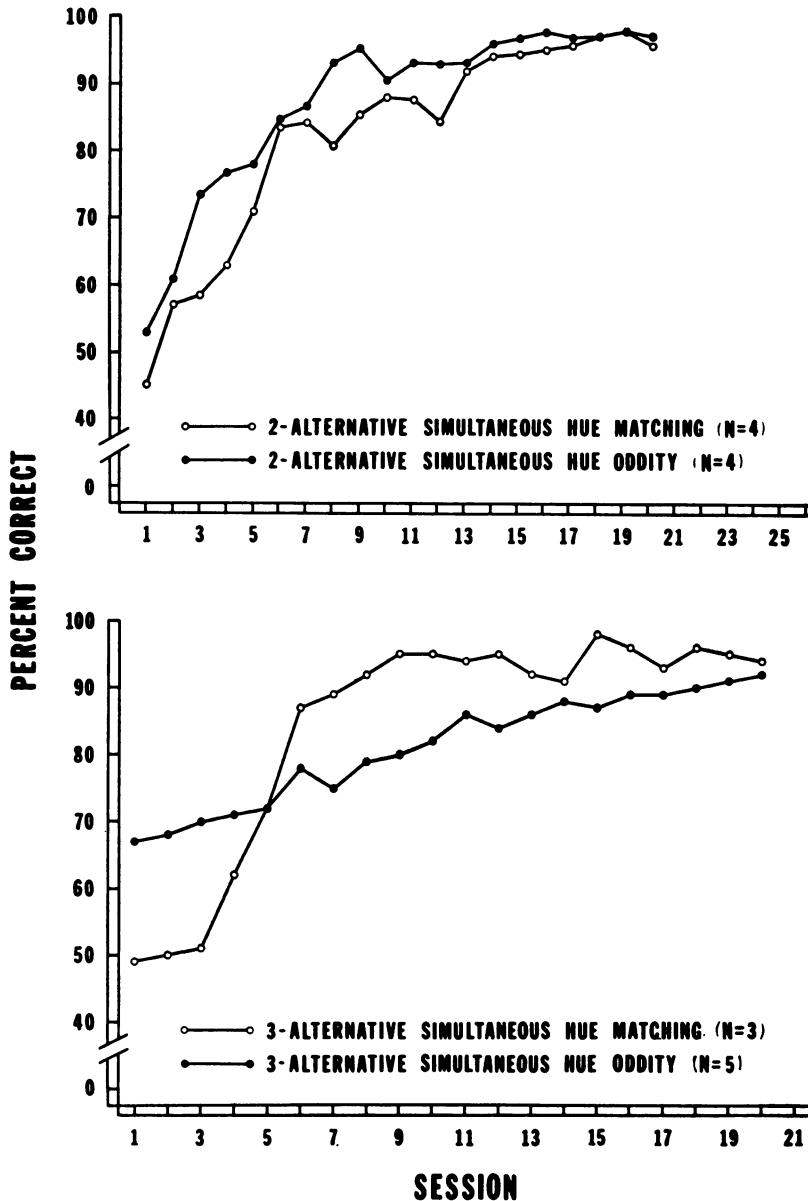


Fig. 3. A direct comparison of acquisition functions for matching and oddity. The data in the upper panel are from an experiment by Zentall and Hogan (1974b) using two stimulus alternatives. The data in the lower panel, showing acquisition functions for three stimulus alternatives, have been redrawn from Cumming and Berryman (1965).

So far, the acquisition of a conditional discrimination using three hues may be described rather simply: (1) In both matching and oddity experiments, the sample stimulus appears to function as a cue that indicates which of two comparison stimuli is the correct choice. These findings suggest that the sample stimulus exercises what might be thought of as an instructional function. (2) Approximately the

same number of trials per rule to be learned are required to reach a steady-state level of performance, regardless of whether the procedure used is matching or oddity. Zentall and Hogan's (1974b) data, showing that two-alternative matching and oddity are learned at the same rate, also support this hypothesis.

A word may now be said concerning the position that animals respond to the entire

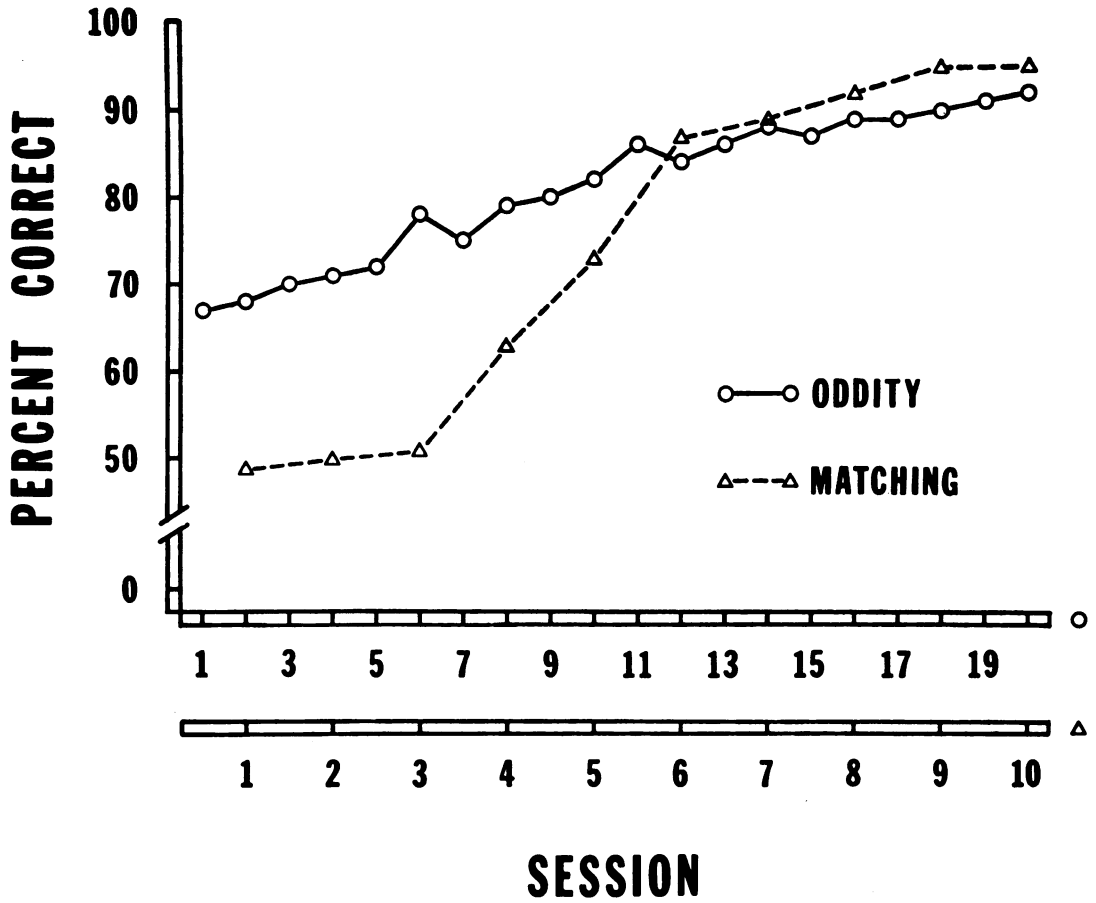


Fig. 4. Per cent correct for two groups of pigeons exposed to either matching or oddity procedures. The scale of the lower abscissa for matching has been doubled because the matching birds have only half the number of S^D rules to learn. The data have been redrawn from Cumming and Berryman (1965, Figure 7, p. 297).

configuration of stimuli on any given trial of a conditional discrimination experiment. The configuration model holds that each three-key combination of hues is learned separately, *i.e.*, the animal learns the appropriate response for each stimulus combination. In this case, data from matching and oddity experiments should show equal rates of acquisition for any fixed number of stimulus alternatives. However, the data in Figure 4 demonstrate that rate of acquisition depends, instead, on the number of S^D rules to be learned.

Most early investigators began to study matching and oddity in the hope of demonstrating that animals were capable of learning a single rule that would apply not only to the training stimuli, but also to novel stimuli. The evidence considered so far suggests that the multiple-rule model provides a more accurate description of conditional discrimination

learning by pigeons. However, the multiple-rule model alone makes no predictions about the behavior of subjects tested for transfer to novel samples. In order to make such predictions, several investigators have added an assumption to the model, which makes predictions possible. We turn now to an examination of that assumption, which has come to be known as the coding hypothesis.

The Coding Hypothesis

Many forms of coding hypotheses have been proposed by investigators interested in theories of perception. However, the form of the coding model that has been most influential in studies of conditional discrimination was originally proposed as an attempt to define the difference between sensation and perception within a behavioristic context. Schoenfeld and Cumming (1963) suggested that the

concept of perception is frequently invoked when the relation between a stimulus and the response that follows is complex. As it is most often used, the term "perception" serves to hide our ignorance concerning the exact form of that relation. Schoenfeld and Cumming held that complex stimulus-response relations are frequently mediated by another response which is seldom observed. The paradigm might be written as $S \rightarrow R_1 \cdot R_2$. The subject presumably reports (R_2) not directly on some specified aspect of the stimulus itself, but instead reports on the occurrence of R_1 , a response (often covert) made directly to the stimulus. The *reporting response* (R_2) is conditional on the occurrence of the *coding response* (R_1).

Perhaps Lawrence (1963) phrased it most clearly in an independent statement of the coding hypothesis.

It is . . . assumed that all stimulus-response correlations are mediated; *i.e.*, the correlation between the response and the proximal stimulus is never direct but always depends upon an intervening event. The conceptual device used to describe this intervening, or mediating, event is similar to the idea of coding. By *coding* the following is meant: If there is a set of objects or events and to each of them a different label is assigned, the labels code these objects or events. . . . It is assumed that the subject makes an implicit, covert response. . . . This implicit response is aroused by factors other than the sensory input under discussion. Nonetheless, it is to be thought of as a form of [operant] behavior. . . . This assumed implicit response operates on the sensory input. It is called a coding response because in interaction with the sensory input it produces a new event or code item which then represents the stimulus. This new event is the "stimulus-as-coded". It is this "stimulus-as-coded" that is directly associated with . . . the overt behavior being measured (Lawrence, 1963, pp. 187-189).

The reporting response might be made either directly to R_1 or to a stimulus produced by R_1 . This question was never treated in detail by Schoenfeld and Cumming or by Lawrence. Most of the evidence that supports the hypothesis that coding is important in match-

ing-to-sample experiments consists either of observations suggesting that different observing responses are made in the presence of different sample stimuli or comes from studies concerned with the transfer of conditional discriminations to novel stimuli. Both lines of evidence are reviewed below.

In one of the earliest studies of matching behavior, Lashley (1938a) used a special jumping stand with three doors. The rats were required to jump to the lateral door, which was covered by a stimulus card identical to the one covering the center door. Jumps to the center door never produced reinforcement. Using crosses and circles as stimuli, Lashley failed to train his rats to match the sample stimulus. In a variation of this experiment, Lashley also failed to establish a discrimination based on the oddity principle.

Lashley's results are interesting for two reasons. First, he used white circles and crosses on a black background, stimuli that are easy for a rat to learn in a simultaneous discrimination. Second, unlike the Cumming and Berryman procedures, Lashley's procedure did not require the rat to make a response to the sample stimulus. The latter finding suggests that animals may not learn conditional discriminations without responding directly to the sample.

The importance of requiring a response to the sample has been demonstrated more recently by Eckerman, Lanson, and Cumming (1968) and by Zentall, Hogan, and Holder (1974). The pigeons in the study by Eckerman *et al.* had more difficulty in learning simultaneous hue matching when no response to the center key (*observing response*) was required than when a response to the sample was needed to turn on the comparison stimuli. These investigators also found that removing the requirement for an observing response after matching behavior had been established seriously disrupted the discrimination. Two of their three birds eventually acquired stable matching behavior again, but only after the birds had developed an overt superstition that seems to have served as an observing response.

The importance of the observing response has also been demonstrated by Maki, Gillund, Hauge, and Siders (1977). They selectively extinguished responses to one of the samples used in the study and found that matching ac-

curacy was reduced only on trials containing that sample.

The data described above suggest that the sample stimulus in matching experiments provides a cue for a chain of behavior that mediates the choice of comparison stimuli. Presumably there is a different chain for each sample. The most direct evidence supporting this hypothesis comes from studies of delayed matching.

In one such study by Blough (1959), a vertical slit between two response keys was illuminated on any given trial by either a steady or a flickering white light. No response was required to this sample stimulus. The sample appeared at the beginning of each trial and remained on for 1 sec. After a specified delay, timed from offset of the sample, the two response keys were illuminated. The comparison stimuli were a steady and a flickering key light identical to the two samples used in the experiment. Responses to the comparison stimulus that matched the sample were reinforced. Four delay intervals, ranging from 0 to 10 sec, were scheduled in random order during each session.

All four of Blough's subjects exhibited stereotyped superstitions during the delay intervals. Two of these birds emitted the same superstitious chain in the presence of both samples, and each of them showed rapidly decreasing accuracy as the delay intervals increased in length.

Blough found that for the remaining two birds, superstitious chains were correlated with the two samples. These sample-specific sequences of behavior seem to have mediated the delay. That is to say, without overt mediation, performance was poor at all but the shortest delays. But as long as the correct superstition occurred, accuracy remained high even when the delay lasted for 10 sec.

In their study of delayed matching, Berryman, Cumming, and Nevin (1963) were unable to detect by visual observation sample-specific superstitious chains mediating the delay interval. However, they reasoned that if there are differential chains mediating the delay interval, such chains must start with the presentation of the sample stimulus, and that inspection of quantitative measures of behavior on the center key would probably reveal sample-specific differences. Five responses to the center key had been required in order to in-

crease exposure to the sample on each trial. The latency from onset of the ratio was computed for each sample. Two of the seven birds showed reliably different latencies (although in different directions) between the green sample and the other two hues. Perhaps other measures of center-key behavior, such as topography and force of pecking, would have revealed sample-specific behaviors for each bird.

On the surface, direct evidence for the coding of hues in matching-to-sample studies would suggest that support for the coding hypothesis is seldom, if ever, found in all subjects. However, it must be remembered that failure to find evidence of coding by direct observation does not necessarily mean that coding has not taken place. No particular form of coding response is required by the contingencies of the matching experiment, and it seems unlikely that coding responses would ever have the same form for all subjects. Perhaps it would be better to study coding using an experimental design that requires a particular topography for each coding response, but only a few such studies have been reported.

Eckerman (1966, 1970) attempted to gain direct experimental control of coding responses by presenting the sample hue on a response key 24.76 cm long. The key was divided into 20 evenly spaced segments and responses to each portion of the key were recorded separately. A hue (506 or 583 nm) transilluminated the sample key. Vertical and horizontal lines served as comparison stimuli in a symbolic matching procedure, with the sample hues indicating which line must be chosen to produce food.

Three groups of birds were used in Eckerman's experiment. In the first group, a peck on either of the two middle segments of the sample key was required to turn on the comparison stimuli, regardless of hue. In the remaining two groups, the locations along the sample key that must be pecked to produce the comparison stimuli differed depending on the wavelength of the sample. In Group 2, the locations were separated by 7.62 cm; in Group 3, they were separated by 15.24 cm. Group 1, for which the locations were identical for both sample hues, corresponds to the common conditional discrimination procedure in which the contingencies do not require a specific form of coding response. However, the proce-

dures used for Groups 2 and 3 do require sample-specific observing behavior.

Eckerman's data show that Groups 2 and 3 learned the symbolic matching problem more rapidly than birds in Group 1. Group 3 acquired the correct behavior more quickly than either of the other two groups. These findings suggest that the sample-specific response topographies required in Groups 2 and 3 served as coding responses mediating the conditional discrimination.

Other investigators have also demonstrated that requiring sample-specific behavior facilitates conditional discrimination learning (Cohen, Looney, Brady, and Aucella, 1976; Lydersen and Perkins, 1974; Perkins, Lydersen, and Beaman, 1973). Perkins *et al.* have also shown that delayed matching is easier for pigeons when sample-specific behaviors are required during the delay interval than when such mediating responses are not required. These studies demonstrate the usefulness of coding responses, but they fail to demonstrate that conditional discriminations must be mediated by coding responses.

Under what circumstances are coding responses utilized? Kamil and Sacks (1972) argued that at least in zero-delay matching, the sample must be coded in some way because the sample stimulus is not present when the choice of comparison stimuli is made. For example, consider two kinds of trials, $R(R^*,G)$ and $G(R,G^*)$, in which red is always on the left. At the time that the subject must choose a comparison stimulus, the exteroceptive stimulus patterns present are identical because the sample disappears as soon as it has been pecked. However, their argument says nothing about how essential coding responses may be when the sample is present at the time of choice. Two transfer studies carried out in Cumming and Berryman's laboratory suggest that samples are coded regardless of whether they remain on in the presence of the comparison stimuli.

In the first experiment, Cumming *et al.* (1965) trained six pigeons to match red, green, and blue hues using a zero-delay procedure. Presumably, using a zero-delay procedure increases the likelihood that the birds will base their selection of comparison stimuli on their response (R_1) to the sample simply because the standard is no longer present. Following 42 sessions of training, three of the subjects

were given 12 additional sessions in which a yellow stimulus appeared whenever a blue one had been scheduled previously.

To describe the results of the experiment, it will be helpful to return to the notation system used in Tables 1 and 2 for specifying stimulus combinations. Consider the trials in which yellow appears as both a sample and a comparison stimulus, $Y(Y^*,R)$ and $Y(Y^*,G)$. Suppose that the subjects have already learned separate sample-specific behaviors (coding responses) for red, green, and blue. The coding hypothesis states that the birds will choose a comparison stimulus, not on the basis of the sample hue itself, but on their response (R_1) to that sample. When yellow appears on the center key, birds are assumed to have no coding response available for yellow. Instead, the birds presumably make one of the coding responses already learned (for red, green, or blue), even though the sample that previously set the occasion for that coding response is not present.

Now suppose that pigeons code yellow samples as red. If red is available as a comparison stimulus, on trials designated $Y(Y^*,R)$, birds should choose the red side key. Since yellow is the correct comparison, matching accuracy should fall to chance level, and again the data come close to the predicted value, assuming that yellow samples are coded as red.

It should be noted that saying yellow stimuli are coded as red is not the same as saying that pigeons cannot tell the difference between yellow and red. They can. On trials in which both red and yellow appear as comparisons, the birds could not fall below chance unless they are able to discriminate between red and yellow comparisons. The fact that pigeons can discriminate red and yellow is also shown by the finding that all birds learned to match yellow stimuli after a few training sessions.

We need not have assumed that yellow would be coded as red. It could have been coded as either green or blue, in which case different predictions for the outcome of transfer tests must be made.

One other point must be raised with respect to how predictions are made from the coding hypothesis. For example, consider what happens when a $B(B^*,R)$ trial is changed to a $Y(Y^*,R)$ trial. Why doesn't the coding hypothesis treat this transfer situation as equivalent to a trial on which all three stimuli are

red? The answer is that the model does not assume that yellow looks like red. Instead, the reporting response (R_2) is based on the properties of the coding response (R_1). It is as if the pigeon does not (or cannot) attend to both the sample and the comparison stimuli, and under these conditions, the coding response serves as a cue when the pigeon responds to the side keys.

Coding also occurs in the transfer of oddity-from-sample to novel sample hues (Berryman, Cumming, Cohen, and Johnson, 1965). Birds were exposed to 20 sessions of simultaneous oddity. The next several sessions were transfer tests in which the only change in procedure was the substitution of yellow stimuli where blue ones had been.

Consider the trials in which yellow appeared both as a sample and as a comparison stimulus. Suppose that green appears as a comparison hue, $Y(Y,G^*)$. The rule that the birds have learned for red samples is "if red, peck green or blue whichever is available". Because green is available, no drop in accuracy is predicted. The data show that the six subjects averaged 94% correct on the last day of training and 96.5% correct on the first day of transfer testing.

Now, suppose that red is available as a comparison stimulus instead of green, $Y(Y,R^*)$. The birds code the trial as $R'(Y,R^*)$. The rule is still "if red, peck green or blue whichever is available". However, neither green nor blue is available, so the coding hypothesis predicts that the bird's accuracy should drop to chance level (50%). The data from the first day of the transfer test show an average of 54% correct on $Y(Y,R^*)$ trials, a figure very close to that predicted by the coding hypothesis. Apparently, a zero-delay procedure is not a necessary condition for coding to occur.

The transfer tests just described constitute generalization tests using a single novel stimulus. A more complete generalization study has been reported by Cohen (1969). Stimuli were presented on only two keys.⁴ Comparison hues always appeared on the right key, and a single response on that key produced the next comparison. Six comparison stimuli were used in all, and the order in which they appeared was randomized. Samples appeared on the left key. The pigeon's task was to produce a succession of comparison stimuli until it found one with

a hue that matched the sample. Then, when both keys were identical, a single peck at the sample produced food.

Only two sample wavelengths were used for the first group of birds; the remaining groups were exposed to either four or six samples. The rate of learning varied inversely with the number of samples used. This suggests that the rate of acquisition of both two- and three-key matching behavior depends on the number of rules to be learned.

Because all six comparison hues were used, regardless of the number of samples employed, an examination of the probability that the bird would peck the sample (reporting response, R_2) as a function of comparison wavelength provides a measure of the development of generalization throughout the course of training. Eventually, new samples were added for birds that began training with fewer than six samples. As predicted by the coding hypothesis, when new samples were added, the pigeons responded to them initially as though they were one of the old samples.

The coding of hues may be viewed as a color-naming problem. Wright and Cumming (1971) identified color-naming functions for the pigeon using a matching-to-sample technique. Six birds were trained on simultaneous matching using stimuli with wavelengths of 512, 572, and 655 nm, equated for brightness based on Blough's (1957) spectral sensitivity curves for the pigeon. After all birds had reached a high level of accuracy, the probability of reinforcement for a correct match was reduced from 1.00 to 0.17, and novel wavelengths appeared on the center key during a few of the trials in which reinforcement was not scheduled. These novel (probe) stimuli were always selected from the range between the two comparison stimuli scheduled on that trial.

The generalization gradients obtained by Wright and Cumming are shown in Figure 5. The three functions are smooth curves, drawn through points representing the mean per cent of side key reports for each comparison stimulus plotted as a function of the wavelength on the center key. The comparison wavelength is shown above each curve.

⁴Although the two-key matching procedure is seldom used, Clark and Sherman (1970) and Boren (1973, Experiment 2) employed variations of Cohen's technique.

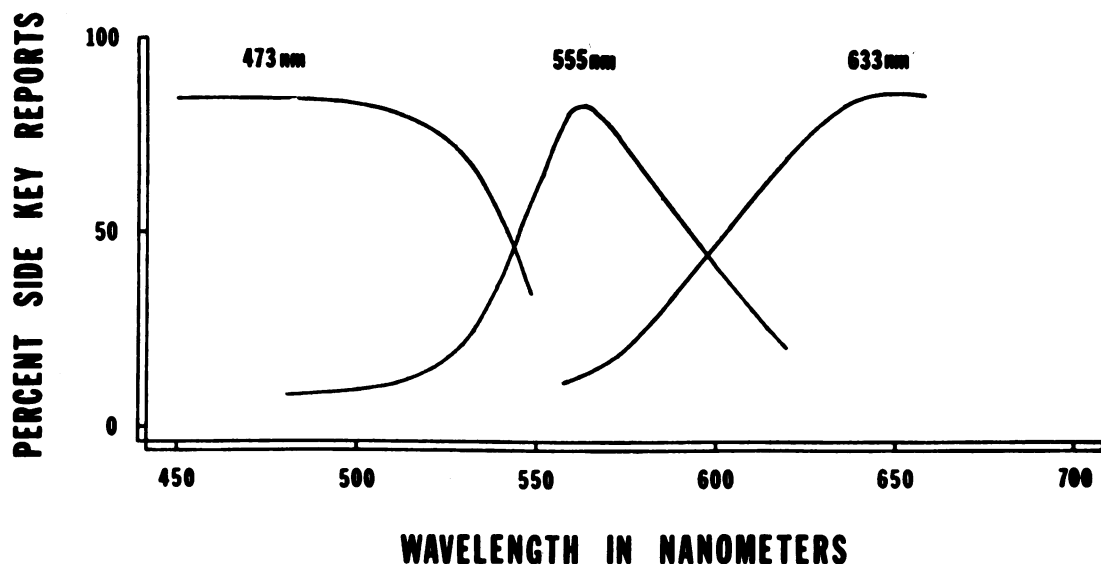


Fig. 5. Color-naming functions for the pigeon. The data have been redrawn from Wright and Cumming (1971) and have been reproduced from Karr and Carter (1970).

The functions share at least two characteristics with human color-naming data (e.g., Beare, 1961, 1963), *i.e.*, they encompass a wide range of wavelengths and are relatively flat on top, with steep slopes near points where a pair of functions intersect. The slopes are not as steep as those of human color-naming functions, but this difference may be due to continued testing in extinction with novel wavelengths. The slopes may decrease as the pigeons learn to discriminate between experimental conditions in which reinforcement is sometimes available and probe conditions in which it is not.

Wright and Cumming suggest that their data represent color-naming functions for the pigeon. The points of intersection are interpreted by them as the boundaries between three hues. Of course, it is possible that their pigeons were bisecting intervals, much as human subjects do in some psychophysical experiments. To test for this possibility, Wright and Cumming retrained the birds using different training stimuli, 473, 555, and 633 nm. If pigeons bisect spectral intervals, the points of intersection of the new functions should shift toward the shorter wavelengths. If the functions represent hues for the pigeon, they should not be altered by using a new set of training stimuli. The data were almost identical under the two sets of conditions. Appar-

ently, Wright and Cumming have succeeded in identifying three distinct hues for the pigeon.

Hues for the pigeon do not correspond to hues for human subjects. One pigeon hue, between 540 and 600 nm, includes the human yellow and part of the green region. A second pigeon hue, for wavelengths longer than 600 nm, encompasses both the human orange and red regions. The third pigeon hue, for wavelengths below 540 nm, includes all of the human blue and violet regions plus a portion of green.

Effects of Intermittent Schedules

Up to this point, we have reviewed only those variables that produce behavioral effects relevant to the coding hypothesis. However, not all investigators have directed their research at the issues described above. Several additional parameters affect conditional discrimination performance.

Using fixed-ratio schedules, Sacks, Kamil, and Mack (1972) and Lydersen, Perkins, and Chairez (1977) have shown that, when more than one response to the sample is required to produce the comparison stimuli, the accuracy of matching and oddity performance increases. The greater the number of required observing responses on the center key, the higher the accuracy. Intermittent reinforcement of observing behavior may facilitate discrimination

merely by prolonging exposure to the sample.

When fixed-ratio schedules of food reinforcement are arranged for correct matches (*i.e.*, correct reporting responses), the effects are opposite. Nevin, Cumming, and Berryman (1963) found that at the beginning of the ratio, errors were frequent. However, near the end of the ratio, accuracy increased to a high level. Mintz, Mourer, and Weinberg (1966) reported similar findings. The data may be interpreted as indicating that when the probability of reinforcement is zero, pigeons no longer attend to the sample. They begin to attend to the hue on the center key only near the end of the ratio shortly before reinforcement is due. This interpretation is also supported by the results of the Nevin *et al.* study, when variable-ratio schedules were employed. Apparently, when the availability of reinforcement is unpredictable, pigeons continue to attend to the samples on nearly all trials. The most important implication of these findings should be obvious. To say that the pigeon has made an observing response (pecked the center key) does not imply that the subject is attending to the sample.

Conflicting results have been reported by Ferster (1960). In his study, Ferster found that matching accuracy was greatest when the requirement for reinforcement was 15 or 20 correct matches or more. Accuracy was lower for short ratios, including FR 1 (continuous reinforcement). Ferster's procedure differed from the procedures of the studies discussed above in several ways. Perhaps the most important difference is that every correct match turned on the feeder light for 0.2 sec. When the schedule for food delivery was FR 1, the feeder light was consistently paired with access to mixed grain, but this is not the optimal method for creating powerful conditioned reinforcers. Instead, when the value of the fixed-ratio is greater than one, the conditioned reinforcers should increase in strength, because approaching the feeder is reinforced intermittently in the presence of the feeder light (D. W. Zimmerman, 1957). And it follows that the greater the effectiveness of the conditioned reinforcer (the higher the ratio), the more accurate the pigeon's matching performance.⁵

Ferster also found that both fixed- and variable-interval reinforcement schedules produced more errors than the fixed-ratio procedure. This may be due to the fact that reinforcement density is affected more by

errors when ratio contingencies are used than when interval schedules are employed. Pigeons may attend to the sample more carefully under ratio contingencies because a failure to do so necessarily postpones the availability of food.

The analysis of Ferster's data may also be useful in understanding the results of a study by Boren (1973). She reinforced correct matches following either a fixed or a variable number of completions of a fixed-interval unit schedule. These second-order schedules (Kelleher, 1966) produced similar numbers of correct matches and errors, a finding that seems to be at variance with the results of Nevin *et al.* (1963) and Stubbs (1968), each of whom found that variable-ratio contingencies produced a higher level of accuracy than a comparable fixed-ratio schedule of food reinforcement.

But, as in the Ferster experiment, every correct match in Boren's study produced either a primary or a conditioned reinforcer. The conditioned reinforcer in this instance was a brief presentation of the feeder light without actual operation of the food magazine. Boren's birds probably did as well under a fixed-ratio schedule as they did under a variable-ratio contingency because the probability of reinforcement (albeit, usually conditioned reinforcement) for a correct match was always 1.00.⁶

⁵The fact that Ferster did not use an intertrial interval may also be important. At the 1968 meeting of the American Psychological Association, J. A. Sherman ("Effects of Fixed Ratio Schedules and Intertrial Intervals upon Accuracy on a Matching-to-Sample Task") reported a partial replication of Ferster's findings, using a two-key procedure similar to that already described in connection with Cohen's (1969) experiment. However, when Sherman used an intertrial interval, matching accuracy was inversely related to the ratio length. Why the intertrial interval affects matching performance in this way has not been clarified. We must also point out that the effects of an intertrial interval are not limited to steady-state performance. Holt and Shafer (1973) reported that their pigeons did not learn to match at all unless an intertrial interval was used. However, Lydersen, Perkins, and Chairez (1977) reported that their birds learned an oddity problem, even though no intertrial interval was employed in their study.

⁶Although the two second-order schedules did produce similar numbers of correct matches and errors, long pauses occurred when the fixed-ratio procedure was in effect. This finding also holds for simple fixed- and variable-ratio schedules (Ferster and Skinner, 1957). Indeed, this was the main point of Boren's (1973) paper.

We find the data reported by Boren and Gollub (1972) more challenging. They investigated the effects on matching behavior of fixed-interval schedules of food reinforcement ranging from several seconds to a few minutes in length. Errors were most likely to occur during the middle of the interval. Although errors did occur at the beginning of the interval, matching accuracy was demonstrably above chance even when the probability of primary reinforcement was zero. Of course, correct matches produced the feeder light for 0.5 sec if no food delivery was scheduled.

What is most puzzling about these data is not the degree of stimulus control observed at the beginning of the interval. That is to be expected whenever conditioned reinforcers are presented every time the correct comparison stimulus is chosen. Rather, it is the nearly complete disappearance of stimulus control in the middle of the interval, and its return toward the end of the interval, that calls for explanation.

At this point, it may be useful to others if we allow ourselves the luxury of a speculative analysis. The interval begins with a pairing of the feeder light with food. This constitutes a reconditioning trial, which should strengthen the conditioned reinforcer. However, all other instances of feeder-light presentation during the interval weaken the effectiveness of the conditioned reinforcer through extinction. After considerable training (successive extinction and reconditioning) it is not unreasonable to believe that matching accuracy drops because the conditioned reinforcer begins to lose its power more quickly.

Accurate matching is always resumed before the end of the interval. Its return may be occasioned by the only stimuli that reliably precede the availability of food reinforcement—those response-produced cues that accompany intermediate or high rates of responding. Except at the lowest rates, Boren and Gollub's data show a very high positive correlation between rate and accuracy. But regardless of what brings about the return of accurate matching, pecking center and side keys *per se* and matching accurately appear to be under the control of different variables. They do not necessarily occur together, especially in fixed-interval or fixed-ratio schedules. We repeat for emphasis, one cannot equate pecking the center key with attention to the sample.

When correct matches are reinforced intermittently, matching-to-sample procedures serve as an excellent animal analogue of human vigilance studies, such as those reported by Holland (1958). Similar procedures may be used with both human and nonhuman subjects, and it appears that for both pigeons and humans, the degree and pattern of vigilance depends on the schedule of reinforcement. But the intermittent reinforcement of correct matches is especially interesting because it offers an opportunity to measure attention independent of the rate of observing behavior.

Studies of Symbolic Matching

We turn now to a more careful analysis of the contingencies that define a correct response in the presence of a given hue. Cumming and Berryman (1965) extended their investigation of the relations between sample and comparison stimulus by requiring their birds to peck blue in the presence of red samples, red in the presence of green samples, and green in the presence of blue samples. This problem, like matching-to-sample, can be solved by learning a set of three S^D rules. Thus, symbolic hue matching is to be distinguished from hue oddity, which requires a set of six S^D rules for solution. Their pigeons learned symbolic hue matching easily, but not as easily as they learned the matching-to-sample task. This finding is difficult to interpret because no transfer data are reported. Cumming and Berryman did not demonstrate that (1) birds actually learn the task by mastering S^D rules and (2) that coding is involved in learning the problem.

Carter⁷ has replicated the symbolic hue-matching study using a zero-delay procedure. Each of four birds received 80 training sessions in which a single observing response terminated the sample and turned on the comparison stimuli. Every correct response operated the feeder, giving the birds access to mixed grain for 3 sec. Errors were followed by a 3-sec blackout. All reinforcement and blackout cycles were separated from the be-

⁷This experiment was described at the 1976 meeting of the American Psychological Association by D. E. Carter. Copies of that report, "Acquisition and Transfer of Symbolic Hue Matching by Pigeons", are available from the author.

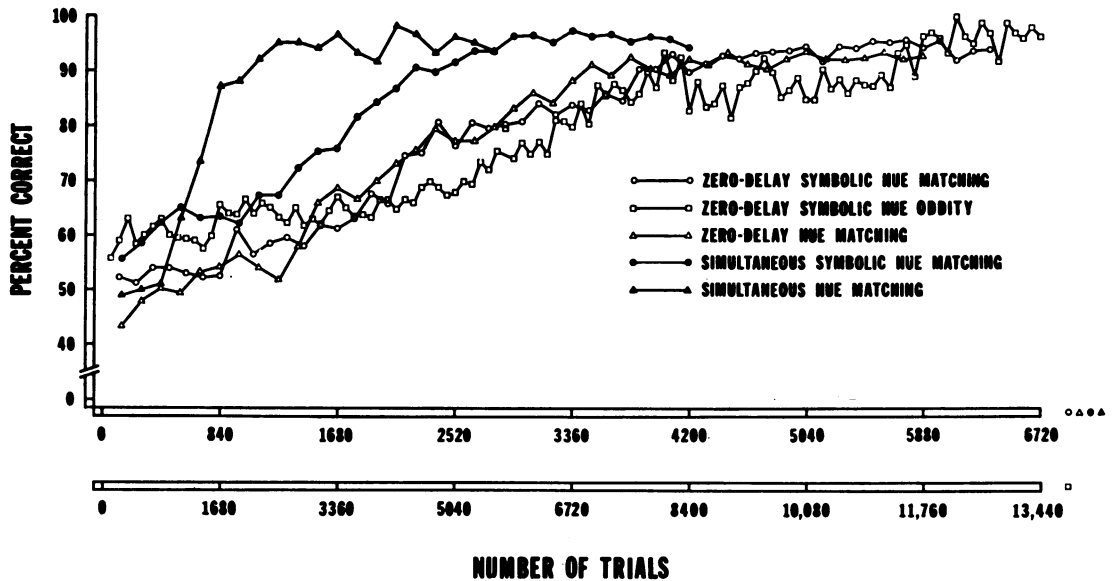


Fig. 6. Group acquisition functions for birds trained using five conditional discrimination procedures: zero-delay symbolic hue matching, zero-delay symbolic hue oddity, zero-delay hue matching, simultaneous symbolic hue matching, and simultaneous hue matching. The lower abscissa has been used to plot the zero-delay symbolic hue oddity data because the task involves six rather than three S^D rules. The upper abscissa applies for the four remaining functions. Sets of data that overlap in the figure require the same number of trials per S^D rule to be learned.

ginning of the next trial by a 15-sec intertrial interval, 10 sec shorter than the one used by Cumming and Berryman. Training sessions were also shorter than those used by Cumming and Berryman; sessions were terminated after 120 trials, rather than 140. A noncorrection procedure was employed, *i.e.*, the birds progressed to the next regularly scheduled trial even when an error occurred.

The results of Carter's study are shown in Figure 6 by the unfilled circles. All birds learned to perform at a high level of accuracy, but the rate of learning is much slower with a zero-delay procedure than when the observing response does not turn off the sample, a finding consistent with the observation that zero-delay matching-to-sample is harder to learn than simultaneous matching.

From the functions shown in Figure 6, symbolic hue matching may be seen to be much harder to learn than matching-to-sample if the sample is present when the bird makes its choice between the comparison stimuli. However, if the sample is turned off when the observing response occurs, the difference in acquisition rates for symbolic matching and matching-to-sample disappears. With the zero-delay procedure, matching-to-sample contin-

gencies may be just as arbitrary as the contingencies in symbolic matching, *i.e.*, both tasks may involve the learning of three S^D rules and nothing more. However, simultaneous hue matching may, indeed, be different from symbolic hue matching in some way not yet understood.

To learn more about the nature of zero-delay symbolic hue matching, Carter conducted a transfer test similar to those carried out by Cumming and Berryman. Yellow stimuli were substituted for blue stimuli at every point in the stimulus sequence where blue would normally have appeared. The results of the transfer test are more complicated than those of the tests described above, perhaps because Carter's birds had been given many more training sessions than birds in the other transfer studies. Whenever yellow appeared on a side key, the birds avoided it and chose the other comparison hue. This tendency makes it impossible to demonstrate that the birds have learned S^D rather than S^A rules. But, Carter's birds learned their task at the same rate of acquisition as that exhibited by zero-delay matching-to-sample birds in the Cumming *et al.* (1965) study. The birds in the Cumming *et al.* study are known to have learned S^D

rules, which led Carter to believe that his birds also used S^D rules. Based on this assumption, it is clear from trials on which yellow appeared only as a sample that yellow was coded as red, just as it was in all other transfer studies.

In analyzing the transfer data in Carter's study, the use of S^D rules was assumed but not demonstrated. In an unpublished study, Carter, Kellman, and Geraghty trained four pigeons using a zero-delay symbolic hue-odddity task, which would require six rather than three S^D rules. All aspects of the procedure were the same as that used by Carter in the symbolic matching study, except that the contingencies were changed to symbolic hue oddity (see Footnote 3). Because there are more rules to be learned, symbolic oddity should be learned more slowly than symbolic matching, *i.e.*, twice as many trials should be required.

The data are shown in Figure 6 by unfilled squares. Note that the figure has two abscissas, the upper one used for zero-delay symbolic matching and the lower one used for zero-delay symbolic oddity. The scale of the upper abscissa is double that of the lower scale. Therefore, the two sets of data will coincide if pigeons require twice as many trials to learn zero-delay symbolic hue oddity as are necessary for mastery of the zero-delay symbolic hue-matching task. Although there is more variability in the oddity data than in the other functions in Figure 6, it is clear that the oddity task is approximately twice as difficult as the zero-delay symbolic hue-matching problem. We interpret these results as supporting the hypothesis that pigeons do learn a set of S^D rules in both symbolic matching and symbolic oddity tasks.

From our analysis so far, it appears that matching-to-sample, oddity problems, and symbolic matching all involve behavior best described by a set of S^D rules. The sample serves an instructional function in that it is a "selector" of discriminations; it functions as a cue to indicate which of two comparison stimuli is S^D . In a sense, matching-to-sample and oddity are misnamed. At least for pigeons, the behavior generated by all three procedures appears to be equally symbolic.

The role that the physical relations between stimuli play in learning a conditional discrimination has been demonstrated most clearly in an experiment that compared matching and symbolic matching with the number of rules to

	HUE STANDARD			LINE STANDARD		
HUE COMPARISONS	(R)	(R)	(G)	(G)	()	(R)
	(G)	(G)	(R)	(R)	(—)	(G)
	(G)	(R)	(R)	(R)	()	(G)
	(R)	(G)	(G)	(G)	(—)	(R)
LINE COMPARISONS	(—)	(R)	()	()	()	(—)
	()	(G)	(—)	(—)	(—)	()
	()	(R)	(—)	(—)	()	()
	(—)	(G)	()	()	(—)	(—)

Fig. 7. The stimulus combinations used for each of the four conditional discrimination procedures in the Carter and Eckerman (1975) study.

be learned held constant (Carter, 1971; Carter and Eckerman, 1975). For each group of pigeons, two samples and two comparison stimuli were employed. The experimental design is illustrated in Figure 7. For each of the two symbolic matching groups, the sample and comparison stimuli lie along different dimensions. One group of birds "matched" red and green samples to vertical and horizontal lines; for the other symbolic matching group, the lines served as samples indicating whether red or green was the correct choice. The stimulus combinations used for these two groups are shown in the lower-left and upper-right panels respectively of Figure 7. The remaining two groups of birds were trained either to match lines or to match hues.

Individual learning curves for each bird have been grouped in Figure 8 so that data from the four conditional discrimination procedures are laid out in the form of a matrix in precisely the same way that the stimulus combinations are shown in Figure 7. In other words, the data shown in the upper-left panel

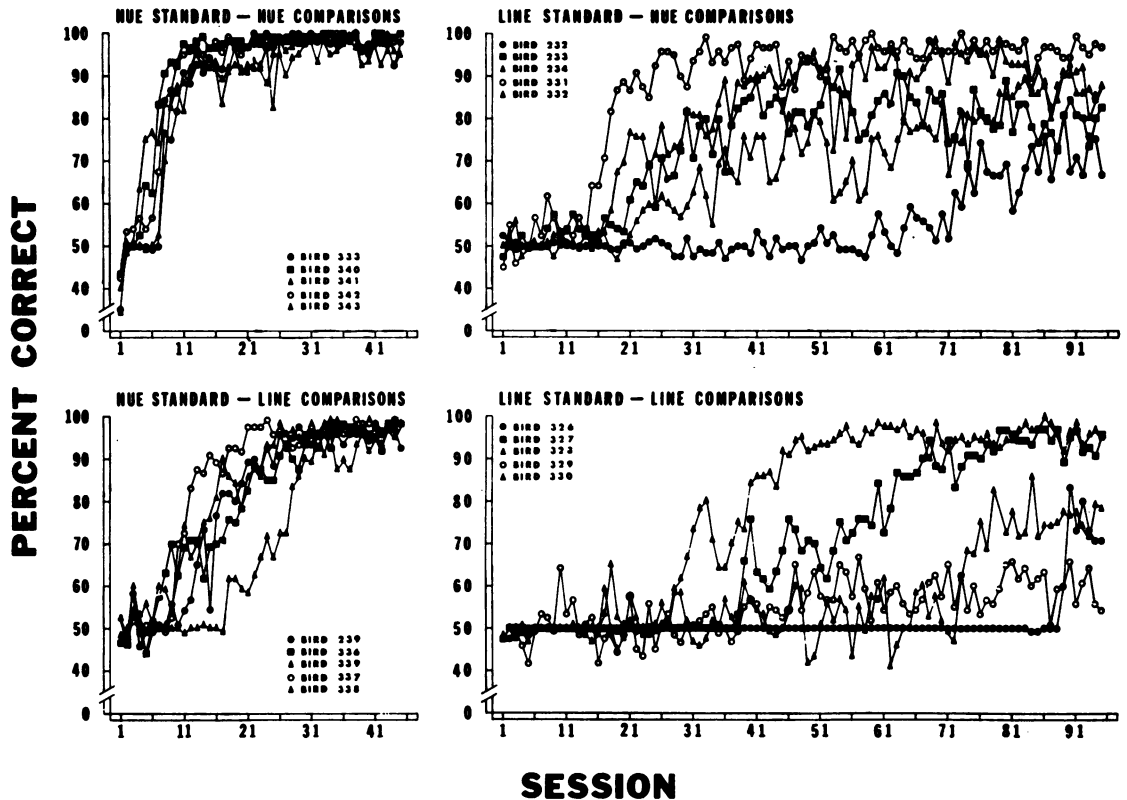


Fig. 8. Acquisition functions for each bird showing the per cent correct for each session for all four conditional discrimination groups in the Carter and Eckerman (1975) experiment.

of Figure 8 were obtained using the stimuli shown in the upper-left panel of Figure 7, and so forth. Data obtained using the same sample stimulus dimension will always appear in the same column; data obtained using the same set of comparison stimuli will always appear in the same row.

Figure 8 shows the percentage of trials on which each bird responded to the correct comparison stimulus for each session. Examination of the acquisition functions provides no support for the notion that symbolic matching is more difficult than matching-to-sample. Although hue matching, shown in the upper-left panel of the figure, is learned most quickly, the line-matching problem, shown in the lower-right panel, is the last to be acquired.

Even in the first session there is evidence in the hue-matching group that the sample stimulus exerts some control over the behavior of each bird. Examination of the acquisition functions for each pigeon shows that they always begin below chance, showing correct re-

sponses on somewhat between 35 and 45% of the trials.

The symbolic matching procedures employed here provide appropriate control data for the observations just described. The sample stimuli are on a different continuum than the stimuli that appear on the side keys. Consequently, there is no reason to expect extinction on the center key to produce any deviation from chance on the first session. The data in the upper-right and lower-left panels of Figure 8 are in accord with this expectation.

However, the contingencies that seem to produce an oddity preference for all hue-matching birds also apply to the line-matching problem. Nevertheless, there is no evidence that line-matching subjects tend to respond to the matching comparison stimulus less than would be expected by chance.

Typically, hue-matching birds show near-chance matching accuracy from the second through the third or fourth session. During this period, they are usually observed to have

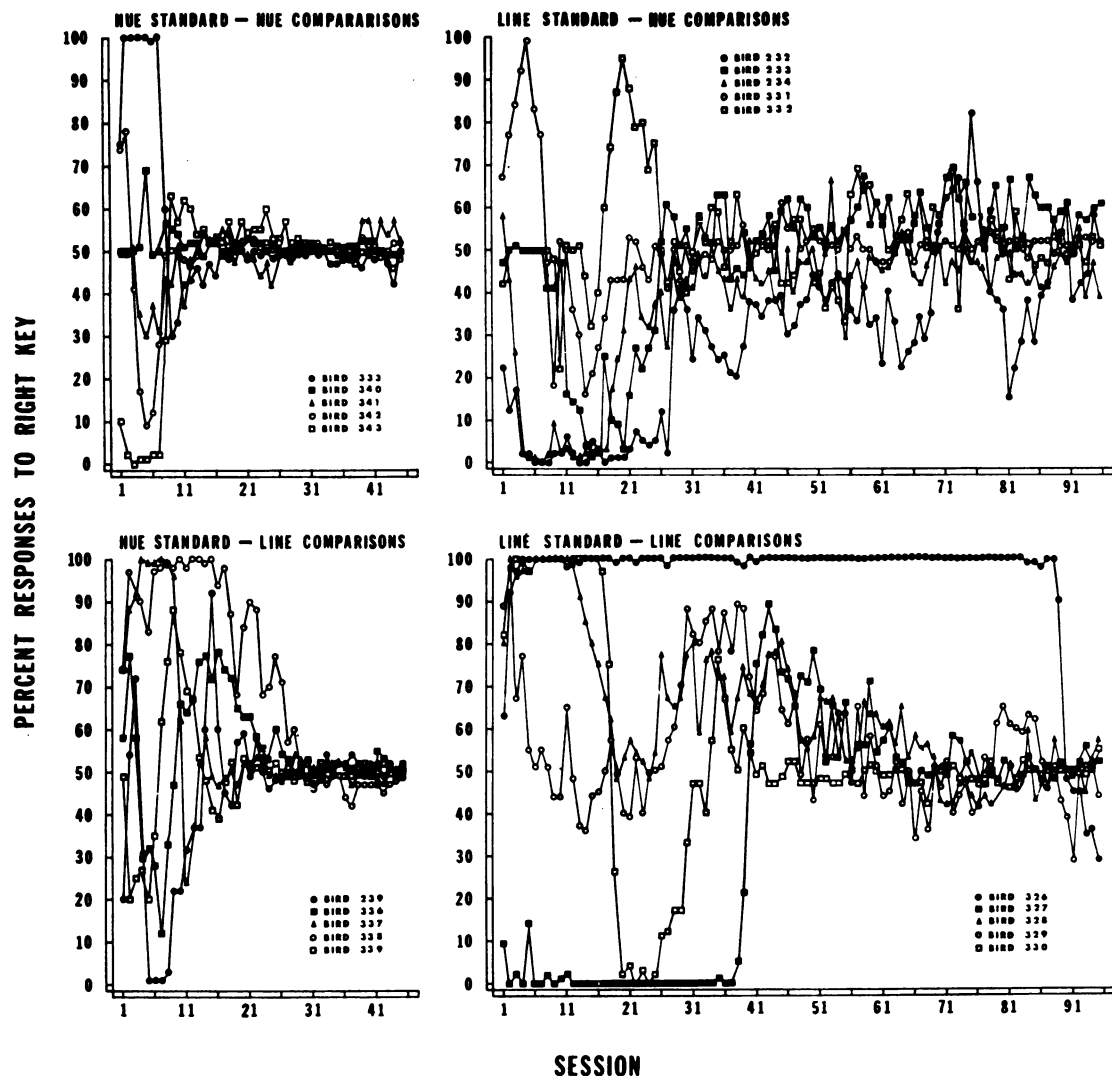


Fig. 9. Position preference data obtained by Carter and Eckerman (1975) using four different conditional discrimination procedures. The percentage of trials on which each bird responded to the right key is plotted for each session.

strong position preferences, followed by weaker color preferences just before learning to match (Cumming and Berryman, 1961, 1965), at least when three stimulus alternatives are used. Figure 9 shows the position preference data for all four groups of birds. The percentage of trials on which each bird responded to the right key has been plotted for each session. Only two of the hue-matching birds show strong position preferences (with two stimulus choices) comparable to those observed in the three choice case.

Although line-matching birds show near-chance matching performance for the first sev-

eral sessions, they do not show stability as great as that observed in hue-matching experiments. With the exception of Bird 326, which exhibits almost exactly chance matching accuracy (and a nearly perfect right-key preference) for nearly 90 sessions, the line-matching birds tend to fluctuate between 40 and 65% correct for several days before clearly showing acquisition. During this period, some birds show strong position preferences and others do not. One bird exhibits a switch from a strong right to a strong left position preference.

Position preferences occur under all four conditional discrimination procedures, and the

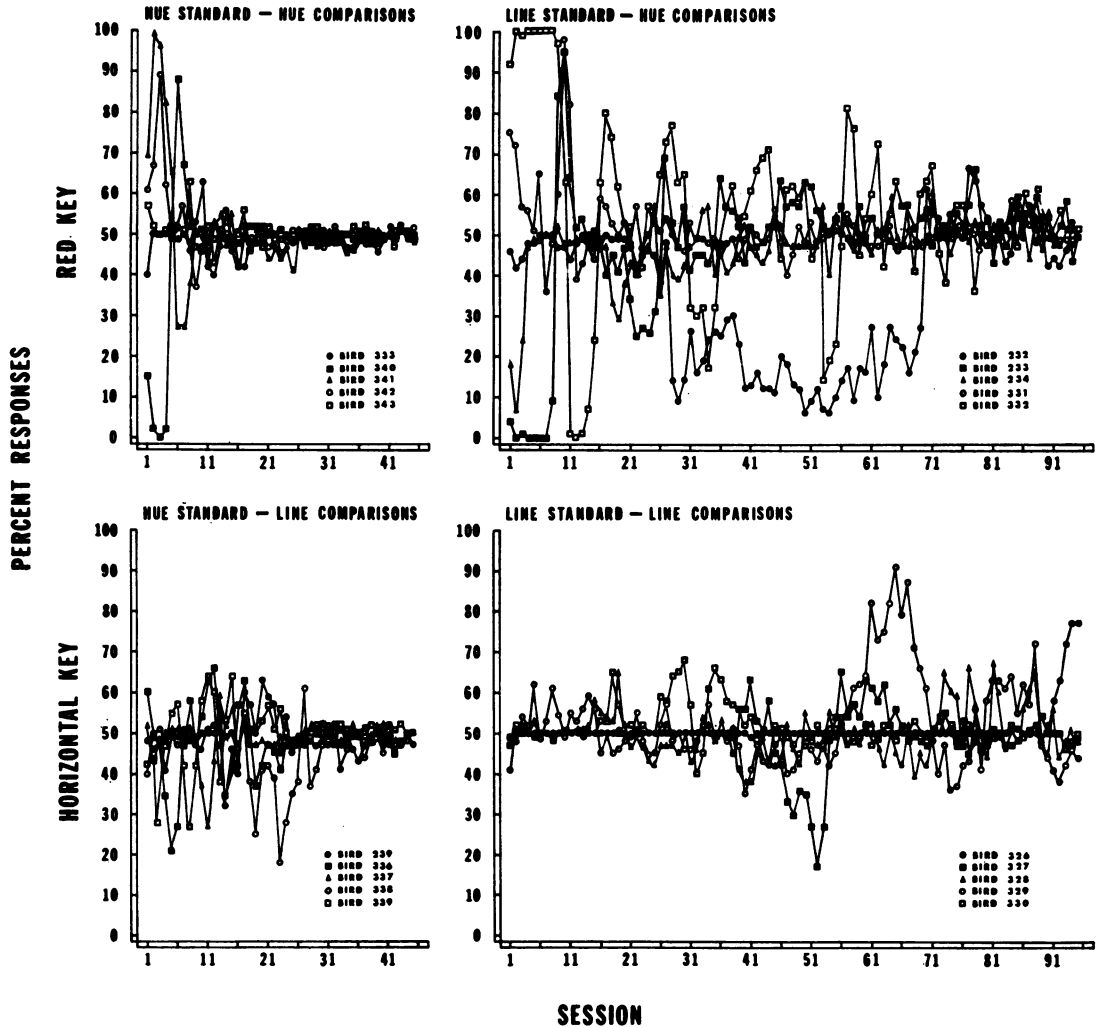


Fig. 10. Stimulus preference data obtained using all four conditional discrimination procedures in the Carter and Eckerman (1975) experiment. In the upper two panels, the percentage of trials on which each bird responded to the red side key is plotted for each session. In the lower two panels, the percentage of trials on which the bird pecked the horizontal line on the side key is plotted for each session.

disappearance of these preferences does not appear to be necessarily correlated with the acquisition of stimulus control. There are a number of instances in which position preferences are followed by stimulus preferences or no preference at all.

The upper two panels of Figure 10 present stimulus preference data for groups of birds trained with hue comparisons. The percentage of trials on which each bird chose a red side key is plotted for each session. Hue preferences occur in both groups, and no one hue is consistently preferred over the other. The data for the two groups using line comparisons are shown in the lower two panels of Figure 10.

The strength of preference for horizontal lines is shown as a function of the number of sessions. Both horizontal and vertical preferences are observed, but the strength never matches that of hue preferences.

The observation that position preferences are more prevalent when three stimulus choices are used than when two stimuli are employed is interesting because it provides some basis for speculation concerning the origin of strong position habits. In three-alternative matching, only two of the stimuli appear on any given trial. Consequently, over any given period of training, a subject is likely to receive more reinforcements for responding to

position than the bird receives for responding to any particular stimulus. Under these conditions, position habits should become dominant over stimulus preferences. When only two stimulus alternatives are employed, either position or stimulus preferences can prevail.

Returning to Figure 8, the relations among the four groups of acquisition functions may be described as follows: (1) For either sample stimulus dimension, groups of birds presented with hue comparisons learn more rapidly than subjects presented with line comparisons. (2) For either comparison dimension, groups of subjects responding to hue samples learn much more rapidly than pigeons responding to line samples.

Both matching-to-sample and symbolic matching problems include two kinds of simple discrimination tasks. First, a successive discrimination between samples on different trials is required. Second, a pigeon must make a

simultaneous discrimination between comparison stimuli on each trial. By comparing the results for birds given conditional discrimination training to data for pigeons trained on simple discriminations, Carter and Eckerman (1975) show how simple discriminations combine to fix the rate at which matching-to-sample and symbolic matching will be learned.

Figure 11 shows the mean percentage correct responses for each session for all conditional discrimination groups and two simultaneous discrimination groups, one discrimination between red and green and the other between vertical and horizontal lines. The upper abscissa has been used for all procedures using lines on the side keys. Because one session on the upper abscissa is equal to 2.5 sessions on the lower abscissa, two sets of data points will coincide if the one involving line comparisons takes 2.5 times as long to learn as the one involving hue comparisons.

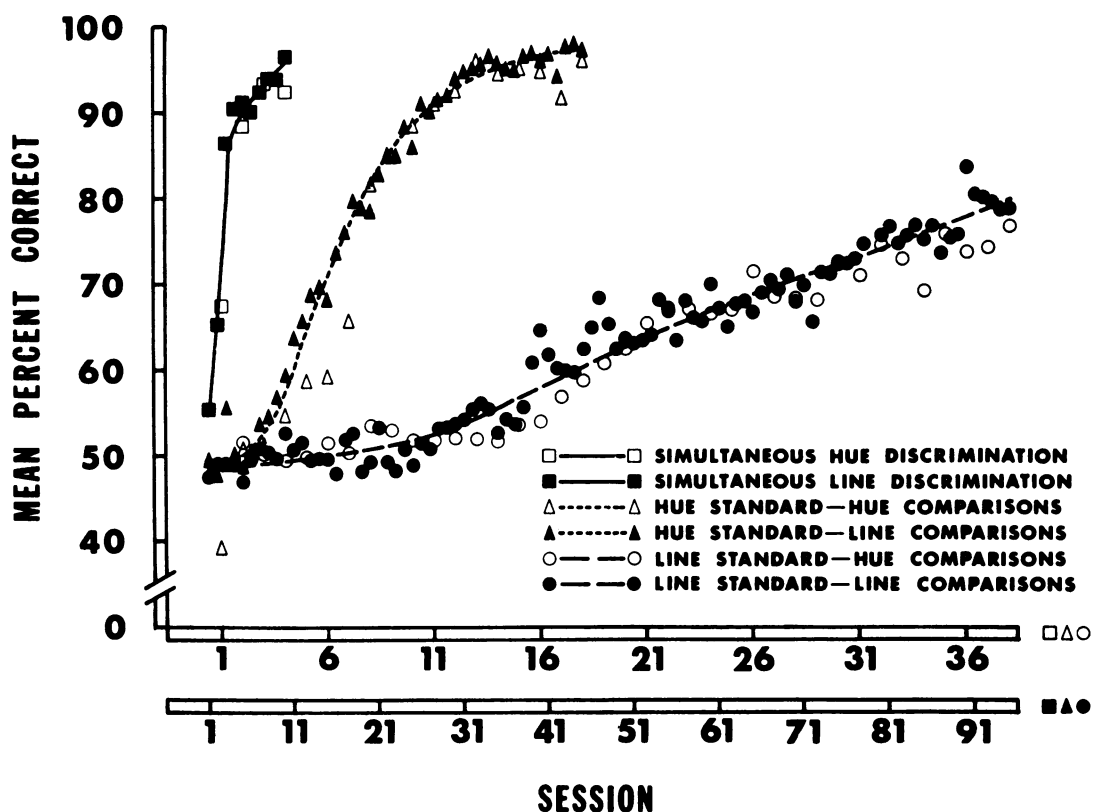


Fig. 11. Mean per cent correct for each session for all four conditional discrimination groups and two simultaneous discrimination groups in the Carter and Eckerman (1975) study. The upper abscissa has been used for all discriminations involving hues on the side keys. The lower abscissa has been used for all procedures using lines on the side keys. One session on the upper abscissa is equal to 2.5 sessions on the lower abscissa. Slightly modified from Carter and Eckerman (1975).

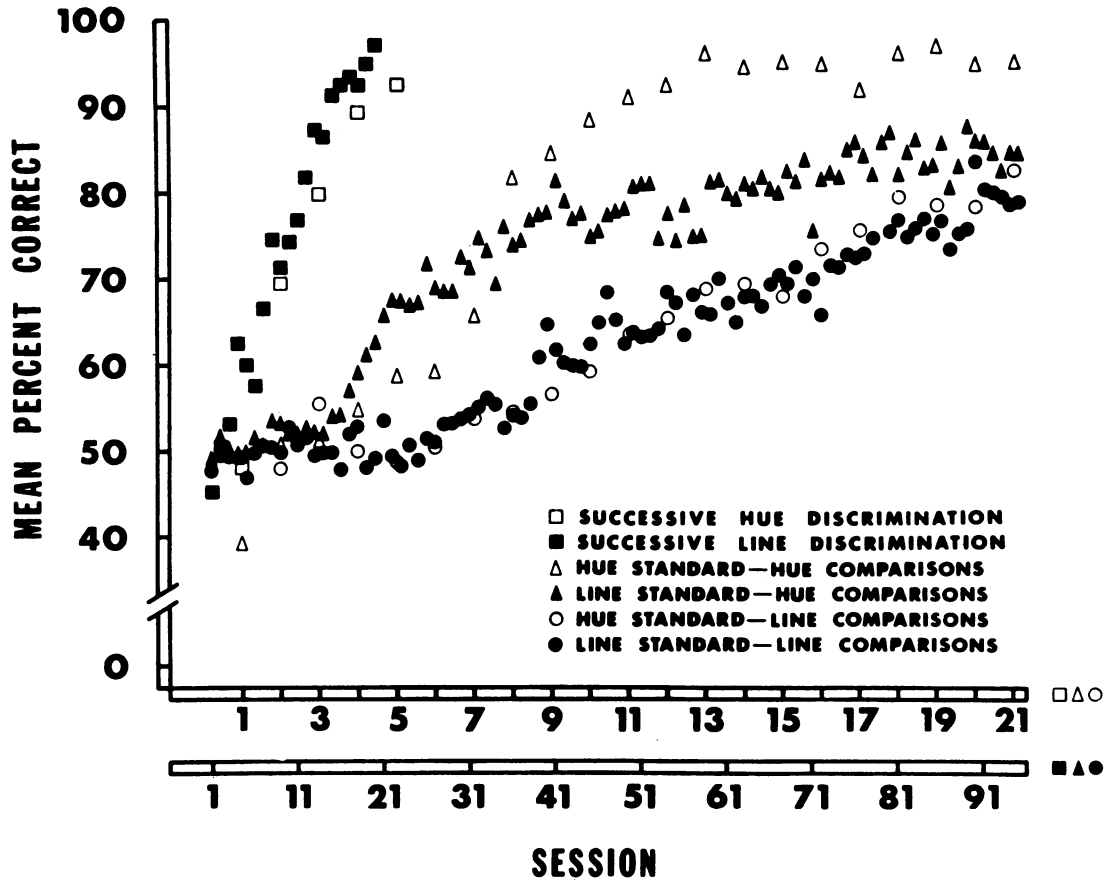


Fig. 12. Mean per cent correct for each session for all four conditional discrimination groups and two successive discrimination groups in the Carter and Eckerman (1975) experiment. The upper abscissa has been used for all discriminations involving hues on the center key. The lower abscissa has been used for all procedures using lines on the center key. One session on the upper abscissa is equal to 4.5 sessions on the lower abscissa. Slightly modified from Carter and Eckerman (1975).

The relationship between abscissas was chosen empirically to test the following hypothesis: the relative difficulties of any pair of discriminations (simple or conditional) bear the same quantitative relationship to one another if the discriminations of that pair differ from each other only in the sample stimulus dimension or only in the comparison stimulus dimension. For the curves in Figure 11, one function of each pair was generated by using hues on the side keys. The other member of each pair was obtained by using lines on the side keys. The data support the hypothesis because the functions fall into three distinct pairs. The center-key stimulus determines the degree of separation among the pairs of curves.

The hypothesis stated above may also hold when pairs of discriminations differ only in the sample stimulus dimension. Figure 12 shows

the mean percentage of correct responses for each session for all conditional discrimination procedures, one group of subjects discriminating between hues and the other between lines on the center key. The upper abscissa has been used for all discriminations involving hues on the center key. The lower abscissa has been used for all procedures using line samples. One session on the upper abscissa is equal to 4.5 sessions on the lower abscissa.

Four of the six functions support the hypothesis. Given a pair of discriminations that differ in no other way, the one having line samples takes 4.5 times as long to learn as the one having hue samples. However, the curves for hue matching and symbolic line matching (line samples "matched" to hues) do not coincide. Indeed, there is no linear transformation that will bring these curves together.

Carter and Eckerman (1975) have shown that the relative rates of learning for matching and symbolic matching may be accounted for by the discriminability between sample stimuli and between comparison stimuli, with the former playing the more important role. Identity between a sample and one of the comparison stimuli appears to play no role for pigeons. Put another way, matching-to-sample is just as symbolic as is the symbolic matching problem. In both paradigms, pigeons learn a set of specific "if . . . , then . . ." rules, with the sample stimulus serving an "instructional" function to indicate which of the comparison stimuli is the correct one.

This conclusion is strengthened by the results of a study by Rodewald (1974). Two groups of pigeons were trained using procedures similar to those used by Carter and Eckerman for their symbolic matching groups. When birds were switched from one procedure to the other, symbolic matching accuracy fell to chance level. The term "symbolic matching" is the accepted name for a specific procedure, but the behavior is not symbolic in the usual sense of the term. The subjects do not learn to treat a specific hue as being equivalent to a specific line orientation. Hogan and Zentall (1977) obtained similar data.⁸

One possible interpretation of these findings is that pigeons can code hues easily, but that for some unknown reason, pigeons are unable to code line orientations. This interpretation is bolstered by the earlier observation that pigeons have great difficulty learning to match geometric forms (Cumming and Berryman, 1965).

The Carter and Eckerman study has been replicated (Cohen, Looney, Brady, and Aucella, 1976) with the addition of groups of birds trained to respond differently to each sample. In the presence of one sample, the birds were required to respond 16 times to produce the comparison stimuli. These observing responses were emitted at a high rate. In the presence of the other sample, observing behavior was governed by a 3-sec DRL contingency. Consequently, the rate of pecking

the center key was very low. Sample-specific differential responding greatly facilitated the rate of learning. In fact, the rate of acquisition for a conditional discrimination with line samples was equal to that of a group of birds learning a problem with hue samples.

Studies of Short-Term Memory

Our analysis of conditional discrimination learning by pigeons has now progressed to the point at which consideration of certain special cases of the paradigm becomes fruitful. Because more investigators have used matching-to-sample to study short-term memory in animals than to study any other problem, we turn to a critical analysis of these experiments.

Blough (1959) appears to have been the first to have used a variable-delay matching procedure with pigeons, and his observations have already been discussed in connection with the coding hypothesis. The same year that Blough's study appeared, Peterson and Peterson (1959) published their classic study of short-term memory using human subjects. Because both experiments involve memory tasks and delay intervals that vary randomly in length, the delayed-matching procedure is often assumed to provide an animal analogue of the Peterson and Peterson procedure.

One series of studies began with a paper by Roberts (1972). In that article, Roberts proposed a decay theory applied to the strength of the trace produced by the sample stimulus. A discussion of the theory itself is unnecessary because Roberts and Grant (1976) have published a detailed account of their position. What is important to note here is that a presentation of the sample was defined as a peck at the lighted center key. Because the strength of the memory trace should vary with the number of presentations of the sample, Roberts required 1, 5, or 15 responses to the sample before initiating the delay interval. He found that the greater the required number of observing responses, the greater the matching accuracy at all delay intervals, a finding similar to that of Sacks, Kamil, and Mack (1972) using only zero-delay intervals. But the results of Robert's study are difficult to interpret because the fixed-ratio requirement is confounded with the sample duration.

Roberts and Grant (1974) replicated the results of Robert's study with the time of sample presentation precisely controlled. Their

⁸Hogan and Zentall also reported that weak "backward associations" may be formed when a zero-delay training procedure is used, a result consistent with the findings of Gray (1966). However, in both studies, all evidence of backward associations disappeared after the first few test trials.

procedure involved the presentation of trials on which sample duration was controlled by timers mixed with trials on which sample duration was under control of the subject. However, the birds continued to peck the sample on both kinds of trials, and just what effect responding to the center key had on matching accuracy is unclear.

We are unwilling to assume that the delayed matching task used with pigeons is analogous to the procedures used to study human short-term memory. Peterson and Peterson (1959) attempted to prevent rehearsal by requiring their subjects to count backwards. There is no such control in most pigeon experiments, and Blough's (1959) data indicate that such controls are needed. In fact, Perkins (1969) showed that when specific behaviors uncorrelated with the sample stimulus are required during the delay interval, the pigeon's ability to match accurately is all but eliminated.

When behavior during the delay interval is uncontrolled, another approach to the study of short-term memory is possible. Carter, Geraghty, and Kellman⁹ have attempted to push the pigeon's memory to its upper limit by manipulating the distribution of delay intervals.

The four pigeons from Carter's study of the acquisition and transfer of zero-delay symbolic hue matching were used (see Footnote 7). Following acquisition of stable performances, a variable-delay interval was introduced between offset of the sample and onset of the comparison stimuli. The exponential distributions of delay intervals were manipulated by altering the probability of zero-delay trial in the following order: 1.00 (baseline), 0.10, 0.50, 0.40, 0.30, 0.20, and 0.10. If a nonzero delay occurred, the probability that the comparison stimuli would come on at the end of any given second during a delay was always the same as the probability of a zero-delay trial. For example, when the probability gate is set at 0.50 and receives an input pulse once every second during the delay interval, one would expect that on half of the trials a response on the center key would pro-

duce the comparison stimuli immediately. Of the remaining trials, one half would be expected to have a 1-sec delay, *i.e.*, one quarter of the total number of trials. In other words, given that an interval had reached a specified length, the probability that the interval would end at that length was always 0.50. The theoretical distributions of delay intervals expected when the probability of a zero-delay trial is 0.50, 0.40, 0.30, 0.20, and 0.10 are shown in Figure 13.

Every sample appeared equally often with the two incorrect hues, and each sample was used on 40 trials per 120-trial session. The position of the correct choice varied randomly from side to side, appearing an equal number of times on each side in a single session. Correct responses produced access to mixed grain for 3 sec; incorrect responses produced a 3-sec blackout. Both reinforcement and blackout cycles were followed by a 15-sec intertrial interval. Because a single response terminated the sample, sample durations were often as short as 300 milliseconds. The birds were exposed to each probability for a minimum of 14 sessions, but exposure was prolonged at each value if the level of accuracy was not stable over the entire period.

When Carter, Geraghty, and Kellman first switched to a variable-delay procedure, they used a probability value of 0.10 in order to measure short-term memory at delay intervals longer than those used in most previous studies. Over the next several sessions, matching accuracy dropped to near-chance levels even on zero-delay trials. These data are shown by the unfilled squares in Figure 14. The function is based on an average across four birds.

The data may be interpreted as indicating that attention is an important factor in delayed matching experiments. When the percentage of trials on which the birds can match accurately (zero-delay trials) suddenly drops to a low value, the subjects no longer attend to the sample, even though some of the trials are identical to those of the original training procedure.

It is important to point out that all subjects continued to peck at the center key with short latencies. Obviously, our insistence that a center-key response should not be equated with attention to the sample is justified. The extent to which attention varies in other studies in the literature is difficult to assess, but it is

⁹This experiment was described at the 1976 meeting of the Eastern Psychological Association by D. E. Carter, J. A. Geraghty, and P. J. Kellman. Copies of a revised version of that report, "Short-Term Memory in the Pigeon: The Distribution of Delay Intervals Controls Attention to the Sample", are available from the first author.

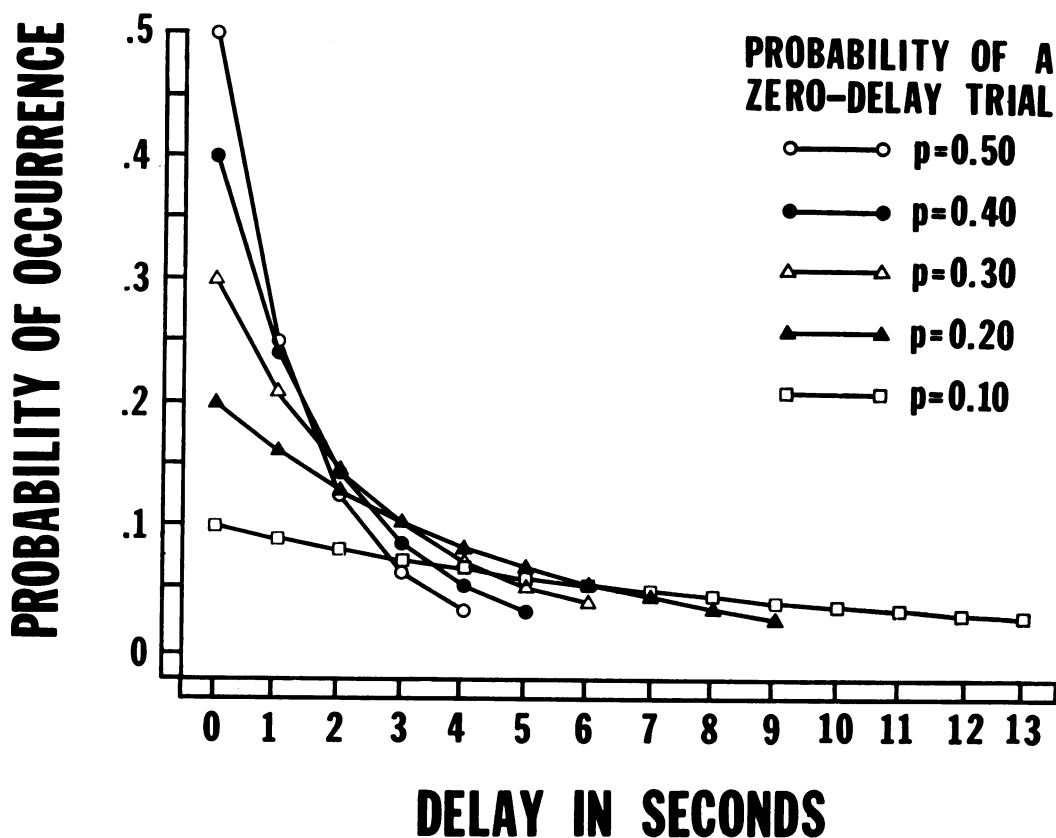


Fig. 13. The theoretical distributions of delay intervals used in the study by Carter, Geraghty, and Kellman. The parameter is the probability of a zero-delay trial.

probably true that previous studies have rarely, if ever, employed procedures that maximize attention to the sample.

Next, Carter, Geraghty, and Kellman increased the probability of a zero-delay trial to 0.5. The birds began to match at levels well above chance. One of these improved after only a few trials, but the other birds required several sessions to reach high accuracy. When all were responding accurately, at least on zero-delay trials, the percentage of zero-delay trials was decreased slowly by changing the probability in steps of 0.10. The data in Figure 14 show that matching accuracy remained high at short delays and was above chance level even for delays of several seconds. Performance was considerably better than that exhibited in most earlier studies of the pigeon's short-term memory, a finding which suggests that few studies to date have succeeded in measuring the pigeon's capacity for short-term memory under optimal conditions.

We cannot leave the topic of short-term memory without commenting on an experiment by Cumming, Berryman, and Nevin (1965). Based on the finding that general activity level varies directly with drive level (Bolles, 1967), and assuming that variable-delayed matching is behaviorally mediated, Cumming *et al.* reasoned that matching accuracy should be highest at low drive levels. When drive level is altered, the rate at which the bird emits its superstitious mediating chain varies directly with drive strength. As a bird becomes more active, the likelihood that some inappropriate behavior will interrupt the mediating chain increases. Because the bird cannot resume its mediation of the delay once the chain is interrupted, matching accuracy should fall to chance on that trial. Consequently, a decrease in drive level should produce an increase in matching accuracy, while an increase in drive should make matching more difficult. Cumming *et al.* lowered drive

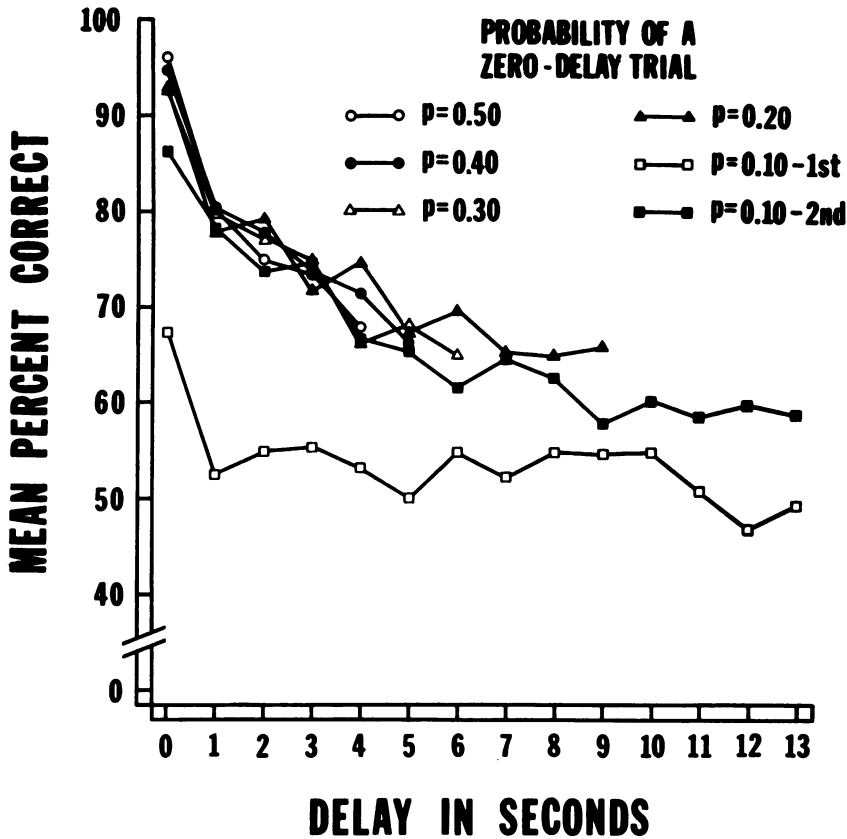


Fig. 14. Short-term memory functions for the pigeon obtained by Carter, Geraghty, and Kellman. The parameter is the probability of a zero-delay trial.

strength by feeding each bird 10% of its running weight 2 hr before the experimental session, and, as predicted, they found that matching accuracy did increase slightly.

Cumming *et al.* may be correct in their interpretation of the data, but an alternative explanation is also possible. Changes in drive strength should affect the activity level not only during the delay interval, but throughout the experiment. Thus, we should predict that the prefeeding operation may have resulted in longer latencies on the center key. Consequently, sample durations would tend to be longer, on average, and the effect of longer sample durations should be an increase in matching accuracy (Maki and Leith, 1973; Maki and Leuin, 1972) whether or not the delay intervals are behaviorally mediated. Therefore, the results of this study cannot be taken as evidence to support the coding hypothesis.

We have not discussed all of the experiments on the pigeon's short-term memory (*e.g.*, see Grant, 1975; Grant and Roberts,

1973, 1976; Farthing, Wagner, Gilmour, and Waxman, *in press*; Maki, Moe, and Bierley, 1977; Shimp, 1976a, 1976b, 1976c; Shimp and Moffitt, 1974, 1977; Smith, 1967; Wasserman, 1976; Zentall, 1973; Zentall and Hogan, 1974a), but most of our comments above apply to many of these studies as well. The design of any experiment that has as its goal the assessment of the memory capacity of an animal should include some means of demonstrating that the subject's attention is as great during the final testing session as it was when a delay interval was first introduced.

The Problem of Attention

The problem of attention has already been raised in connection with the interpretation of short-term memory data. However, other data discussed earlier may also be relevant. For example, an examination of the individual learning functions for hue-matching birds (upper-left panel of Figure 8) and for line-matching birds (lower-right panel) suggests that pi-

geons normally attend to hues even during the first training session. This is shown by the presence of an oddity preference. The curves obtained from the line-matching group do not show an oddity preference. Here there is no evidence that pigeons attend to vertical and horizontal lines during the early part of training. Why this should be the case is unclear, but it does suggest that if attention could be controlled, we might still find that pigeons could learn to match lines as easily as they learn to match hues.

One technique that facilitates matching is the training of sample-specific behaviors that can serve effectively as coding responses (*e.g.*, Cohen, Looney, Brady, and Aucella, 1976; Eckerman, 1966, 1970). That this technique involves attention is obvious, in the sense that attention may be defined as being synonymous with stimulus control (Terrace, 1966). However, a definition of attention with a strict behavioral base fails to provide the conceptual framework necessary to predict which procedures will enhance the learning of conditional discriminations and which will not.

Another procedure especially useful in the study of attention seems to have been developed independently by Maki and Leuin (1972) and by Farthing and Opuda.¹⁰ The pigeon's task is one that involves two kinds of samples, element samples and compound samples. In the most common version of the procedure, the four element samples are a blue key, a red key, a white vertical line, and a white horizontal line. The lines appear on a dark background. Four compound samples are produced by superimposing each of the lines on each of the background hues. Only elements appear on the side keys, *i.e.*, the comparisons are always one of two stimulus pairs, blue and red or vertical and horizontal. On trials having element samples, the bird must match a physically identical comparison stimulus, and the match requires attention to a single stimulus dimension. However, on trials having compound samples, the pigeon must peck the side key on which is projected only one element of the compound sample. Whether the matching element will be a line or a hue is unpredict-

able. Because the comparison stimuli are never presented until the sample is turned off, the subject must attend to and remember both dimensions of the compound on the center key.

Typically, pigeons have greater difficulty matching accurately when the sample contains two elements. However, before we can conclude that the use of a compound sample reveals a rather low limit on the pigeon's capacity to process information, we must examine some other possible interpretations of the data. Maki's most recent work (Leith and Maki, 1975; Maki, Riley, and Leith, 1976) has been directed at determining what factors are responsible for the decrement in performance observed when compound samples are used. A number of possibilities have been ruled out, including a decrement due to stimulus generalization.

If we assume, for the moment, that Maki's pigeons have learned a set of "if . . . , then . . ." rules, another possible explanation for the "shared-attention" effect becomes obvious. Each of the four compound samples requires two rules, while element samples require only one. Thus, the task as we have described it requires a total of 12 rules for mastery, not eight. Because each of the eight samples is always presented an equal number of times, the pigeons have only half the number of opportunities to learn each of the eight rules that apply to compound samples, as compared to the number of opportunities available for learning rules that apply to element samples. Thus, investigators who argue that the performance decrement observed with compound samples results from the requirement that the birds attend to and remember two stimulus dimensions instead of one, must demonstrate first that the behavior has reached a true steady state. Otherwise, we cannot rule out the possibility that birds match at a lower level of accuracy with compound samples simply because they have not had sufficient training to master the problem completely.

We are not suggesting that either Maki and his coworkers or Farthing and Opuda have been too hasty in concluding that their birds had achieved steady-state performance. Their subjects received extensive training. For example, the study by Maki *et al.* (1976) used birds previously given 68,800 trials in various matching tasks. We simply point out here that steady-state methods require stringent criteria for

¹⁰This experiment was described at the 1973 meeting of the Eastern Psychological Association by G. W. Farthing and M. J. Opuda ("Selective Attention in Matching-to-Sample in Pigeons").

deciding that complex discrimination tasks have been mastered or that performance cannot be expected to show eventual improvement. Such criteria should be stated explicitly, and the behavior that meets those criteria should be reproducible in studies that involve the experimental manipulation of steady states (Sidman, 1960, pp. 257-258).

Single-Rule (Concept) Learning

The evidence reviewed above strongly suggests that, at least with the conditional discrimination procedures in common use, pigeons learn a set of sample-specific "if . . . , then . . ." rules. We turn now to the question of whether there are conditions under which pigeons master matching and oddity problems by learning a single rule, that is, what some investigators have called abstract concepts.

Malott and Malott (1970) summarized a series of experiments which they interpret as showing concept learning. Pigeons are placed in a chamber containing a single key, the two halves of which may be lighted independently. Both halves may be the same hue or two different hues may appear on the key at the same time. Responses on the key when both sides are identical (red-red or violet-violet) were reinforced; responses on the key when two different hues were present (red-violet and violet-red) went unreinforced. All four birds learned the discrimination.

The fact that the problem was learned does not demonstrate the acquisition of a matching concept. The birds could just as easily have learned how to respond to four separate stimulus configurations. In order to test between the configuration model and the single-rule (concept) model, the birds were presented with four new configurations (blue-blue, yellow-yellow, yellow-blue, and blue-yellow). Response rates were measured in the presence of each of the novel configurations. Reinforcements were never given during the transfer test. Three of the four pigeons pecked more often at the blue-blue and yellow-yellow configurations, evidence taken by Malott and Malott as indicating that a matching concept had been learned. By reversing the reinforcement contingencies, Malott and Malott were also able to obtain data that suggested to them that pigeons were capable of learning a nonmatching concept.

Malott, Malott, Svinicki, Kladder, and Ponnicki (1971) argued that the results of such experiments cannot be explained in terms of stimulus generalization, but another basis for solution of the problem is possible. Without attending to color at all, birds that had learned to peck at a circle, but not at a pair of semicircles, could easily be mistaken for birds that had learned to match.

Zentall and Hogan (1975) suggested that the best test for concept learning must include a transfer test using stimuli along a dimension orthogonal to the training dimension. They also argued that the most sensitive measure of transfer is the rate of learning of a second problem. Consequently, Zentall and Hogan continued to reinforce correct responses during the transfer test.

Using Malott and Malott's single-key procedure, they trained one group of birds to peck at configurations containing a single hue (matching condition), while a second group was trained to peck configurations having two hues. Instead of using novel hues in the transfer test, the pigeons were exposed to a matching or a nonmatching problem based on brightness. Half of the birds originally exposed to the hue-matching problem were trained on the second matching problem and the other half were transferred to the nonmatching problem. Likewise, the original nonmatching subjects were divided into two subgroups, one of which was given a second nonmatching problem while the other subgroup was shifted to matching.

If concepts are transferred to a new stimulus dimension, the birds shifted from one procedure to another should learn the new problem more slowly than birds that were not shifted. Examination of Figure 4 in Zentall and Hogan (1975) suggests that birds shifted from a nonmatching to a matching problem learn more slowly than the other three groups. There appears to be no difference between the other shifted group and the two nonshifted groups. Zentall and Hogan view these data as supporting the occurrence of concept learning. We must point out that in order to show positive transfer from one discrimination problem to another, two essential control groups must be added to the experimental design. One group would receive only brightness matching training while the other naive group would be exposed to a brightness nonmatching problem.

Positive transfer, indicating that a concept had been learned, would be shown only if Zentall and Hogan's two nonshifted groups learned more rapidly than the animals in the control groups we have suggested.

Two other transfer experiments by Zentall and Hogan (1974*b*, 1976) as well as a similar study by Farthing and Opuda (1974), also lack appropriate control groups. Both studies used the standard three-stimulus procedure to study matching and oddity. Zentall and Hogan's (1976) most recent experiment involved transfer from problems using geometric forms to hue matching or hue oddity. No control groups trained only on hue problems were included, but Carter and Eckerman (1976) employed data from Zentall and Hogan's (1974*b*) paper to obtain curves for naive birds trained to select either the matching or the odd hue. The procedures used in the two experiments appear to be very similar.¹¹ Carter and Eckerman's statistical analysis showed that the superiority of nonshifted over shifted subjects was due entirely to negative transfer. This finding leads us to suspect that the significant effects described in Zentall and Hogan's (1974*b*, 1975) first two papers may also result from negative transfer. We cannot be sure without the appropriate control data, but if we are correct, it becomes clear from an examination of Figure 4 in both papers that the negative transfer is confined largely, if not entirely, to the group shifted from oddity to matching. We are at a loss to explain the lack of negative transfer when birds are shifted

from matching to nonmatching or to oddity tasks. Zentall and Hogan's (1976) paper does not present enough data to determine whether the negative transfer is unidirectional.

Zentall and Hogan's (1976) failure to demonstrate positive transfer in their nonshifted groups leads us to believe that what is claimed to be successful transfer of matching and nonmatching concepts described by Malott and Malott (1970) is limited to the training dimension. In this sense, their pigeons did not learn generalized matching and nonmatching concepts.

Urcuioli and Nevin (1975) devised another technique, which they suggest produces concept learning. A trial began with only the center key lighted. When the pigeons pecked the sample, only one comparison stimulus was presented. If it was the correct (matching) comparison, a single peck on the lighted side key was reinforced. However, if the observing response produced an incorrect comparison, the correct stimulus would appear 4.8 sec later, provided that the bird had not made an incorrect response. Responses to the incorrect comparison stimulus reset the delay interval. The incorrect side key was always darkened when the correct stimulus appeared on the opposite side key.

Following 36 training sessions, Urcuioli and Nevin conducted a series of transfer tests using two novel hues, blue and violet. Over the series of tests, 16 pairs of hues consisting of at least one novel hue were presented. Only two of these pairs contained matching stimuli (blue-blue and violet-violet). If the pigeons did learn a general matching concept, the latency of pecking the side key should be short, a finding that holds across both pairs of hues for all three subjects. With either stimulus pair, the coding hypothesis predicts long latencies if the sample is coded as one of the training hues (red, green, or yellow), and only a novel comparison hue is available. Clearly, the single-rule (concept) model leads to a correct prediction, whereas the coding hypothesis does not.

Urcuioli (1977) has also studied the acquisition and transfer of oddity-from-sample. The procedure was analogous to the one used by Urcuioli and Nevin, except that the contingencies were changed from matching to oddity and a different set of training hues was used. During the transfer test, latencies to matching

¹¹In a personal communication (January 22, 1976), Zentall pointed out some differences between the procedures used in these studies (Zentall and Hogan, 1974*b*, 1976), which may make Carter and Eckerman's (1976) choice of control data inappropriate. In their first study, Zentall and Hogan used a standard Lehigh Valley three-key pigeon chamber (model 1519D) with the keys widely separated. In their second study, the keys were square paddles placed as close together as possible. The first study also used White Carneaux pigeons, the second experiment used birds obtained from a local supplier, and these were of mixed stock. Zentall has also suggested that the use of naive birds trained on hue matching or hue oddity does not provide an appropriate control because these groups "do not control for nonspecific transfer effects resulting from added experience". Zentall may be correct, but if he is, a more suitable control must be found. If an appropriate control cannot be devised, and its adequacy assessed independently of the present problem, it may never be possible to use rate of learning of a second task as a measure of concept learning.

pairs of novel stimuli were long, but when nonmatching pairs of stimuli appeared, the birds responded quickly to the odd comparison hue.

Urcuioli and Nevin's data are especially difficult to interpret because their transfer tests were conducted over several days, during which the reinforcement contingencies remained in effect. To the extent that the pigeons had begun to learn to respond to the novel stimulus pairs, the results of their studies are biased in favor of concept learning. While the results of the transfer tests carried out in Cumming and Berryman's laboratory are also subject to the influence of maintained reinforcement, we must point out that one obtains evidence for coding in spite of the prevailing contingencies. Just how quickly reinforcement comes to play a role in Urcuioli and Nevin's studies is unknown. In both experiments, the results of the early transfer trials were consistent with the overall findings.¹²

Although the data described in this section provide no unequivocal evidence that pigeons learn generalized concepts of matching and oddity, we are unwilling to assume that pigeons cannot learn such concepts. The procedures normally used to establish matching and oddity learning sets with nonhuman primates and with human children (Harlow, 1949) differ from those used with pigeons. With Harlow's procedure, it is commonly believed that subjects could never learn a set of sample-specific rules, because every few trials a new set of stimuli replaces the old set. In other words, it is assumed that the learning set procedure differs from those reviewed above in that the matching or the oddity principle provides the only possible basis for learning.

A careful analysis of the Harlow procedure reveals an error in logic. In most instances, research on matching and oddity learning sets involves the use of the Wisconsin General Test Apparatus. The stimuli most often used are common household or laboratory objects, which are displaced by the subject in order to obtain reinforcement. Each day a new pair of stimuli is chosen, and it is assumed that trans-

fer from one session to another indicates that the subject is responding to a relationship between stimuli.

Several hundred stimulus objects may be needed for a single experiment, but while shape, size, and other stimulus characteristics vary from session to session, only a few distinct hues are available. A subject could solve a matching problem by learning a small number of S^P rules, because each hue is repeated many times during the experiment. All other information in the stimulus array may be disregarded.

Carter and Taten¹³ are the only investigators who have attempted to establish a matching-to-sample learning set in pigeons by using Harlow's procedure. Their birds were exposed to 72 pairs of stimuli consisting of a geometric form on a colored background. Both hue and form elements were repeated during training, but they were never repeated in the same combination. Sessions consisted of 120 trials. Occasionally, hue was the only relevant cue, while for other sessions, only form was relevant. During most sessions, either dimension could be used as the basis for solution.

The procedure, including all temporal parameters, is illustrated in Figure 2. The correction procedure shown in the figure was not instituted until Session 19, when Carter and Taten altered the programming in order to break up the strong position habits that had developed. Under the correction procedure, only the choice made on first exposure to a trial was counted as a correct response or an error. However, each trial was repeated until the pigeon earned a reinforcement.

All birds learned quickly, once the correction procedure had been introduced, but they did so only on the basis of hue. This may be seen in Figure 15, which shows the acquisition data for each of the three subjects. During eight of the sessions, both of the stimulus choices had identical hue backgrounds. In these cases, marked in the figure with arrows, form provided the only basis for solution. In no case does matching accuracy rise significantly above chance, even though many of the other matching problems were solved easily.

¹²A more complete analysis of Urcuioli and Nevin's work was presented at the 1977 meeting of the Eastern Psychological Association by D. E. Carter. Copies of that report, "Three Models of Conditional Discrimination Learning: What Do Transfer Data Mean?", are available from the author.

¹³This experiment was described at the 1977 meeting of the American Psychological Association by D. E. Carter and B. M. Taten. Copies of that report, "Matching Learning Sets: Rule Rather than Concept Learning by Pigeons", are available from the first author.

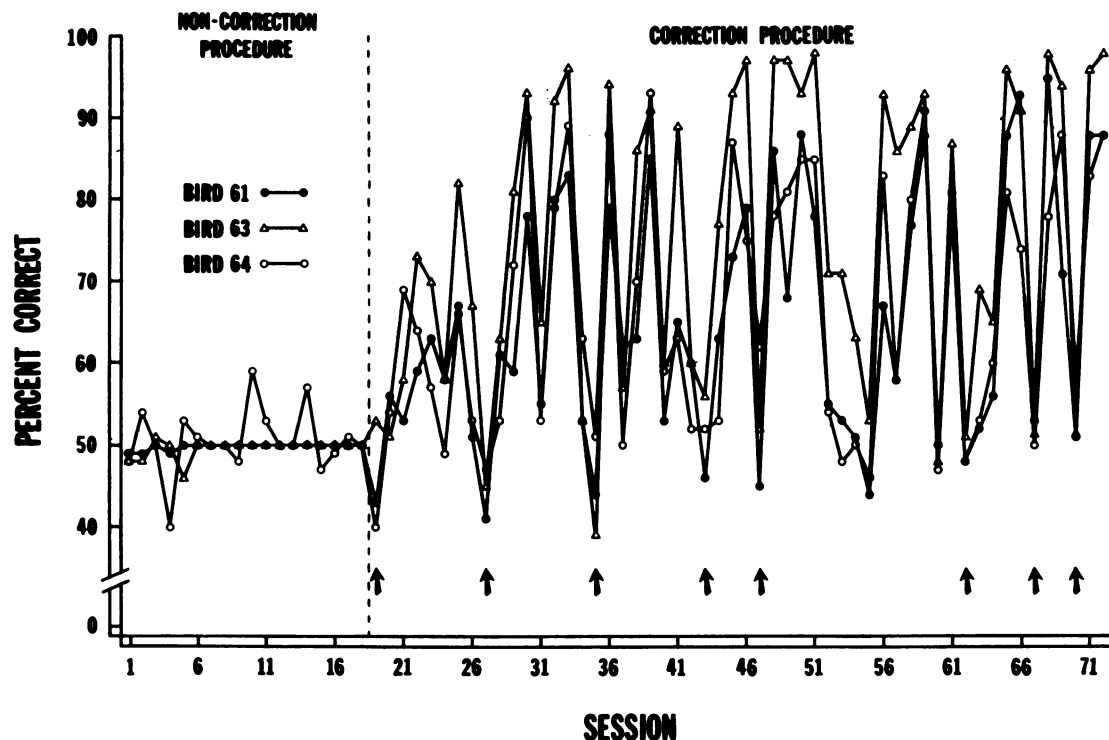


Fig. 15. Acquisition functions for the three pigeons in Carter and Taten's study of the formation of matching-to-sample learning sets. The per cent correct scores based on the first exposure to each trial are shown for every training session. Every session employed a new pair of compound stimuli. The arrows indicate data obtained when form was the only basis for solution of the matching problem.

A careful analysis of the data revealed that hues were categorized, and apparently one rule was learned for each group of similar hues. When the hue backgrounds were similar, but not identical, the pigeons had great difficulty performing above chance level. The findings are similar to those of Wright and Cumming (1971), but the color-naming functions cannot be compared directly because Carter and Taten did not use spectral stimuli.

In contrast to the studies cited above, Honig (1965) appears successfully to have established a discrimination based on the degree of difference between stimuli. The work is related to matching because Honig's pigeons were rewarded for pecking one key, say on the left, if the two available keys were lighted with the same hue. Several identical hue pairs were used to indicate the availability of food. No single wavelength could have served as an S^D . Several nonmatching pairs of hues were also used to indicate that the key in the other position was correct. All birds eventually learned the discrimination based on a dimension of

stimulus difference, and the behavior was successfully transferred from hue differences to brightness differences. The critical features of Honig's procedure, which produce transfer to an orthogonal stimulus dimension, have not been completely isolated, and the technique seems not to have received the systematic study it deserves.

Conclusions

Both the multiple-rule model and the coding hypothesis appear to be useful models for the description of conditional discrimination learning by pigeons. Together, they provide a conceptual framework consistent with almost all of the available evidence. Nevertheless, some important questions remain unanswered.

Most important, since the coding response, R_1 , usually goes unobserved, its existence must be inferred from behavioral data. While it seems compelling to us to speak of coding, there is little or no evidence that the coding event possesses the properties of a response. Perhaps it is better to refer to the "coding

event", leaving open the possibility that coding may be central, rather than behavioral.

A demonstration that behavior can mediate conditional discriminations (e.g., Cohen, Looney, Brady, and Aucella, 1976; Eckerman, 1966, 1970) does not tell us that coding must be behavioral. However, it may eventually be possible to identify the variables that determine the efficacy of mediating behaviors specifically reinforced by the experimenter. The crucial question, of course, is whether or not those same variables have the same effect on conditional discriminations in which the coding event goes unobserved. The answer to this question may tell us a great deal about the functional relations between the mediating event and the choice of comparison stimuli, but we may never be able to determine the true nature of the coding event.

There is now enough evidence supporting the coding hypothesis for us to concern ourselves with another important question—under what conditions does coding take place? Are all discriminations mediated, or does the pigeon have the capacity to learn to respond to stimuli by any one of several processes? We can offer no definite answers here. However, the conditional discrimination paradigm may be manipulated parametrically to match many of the requirements of both human and animal studies of memory, attention, recognition, and other kinds of information processing, allowing us to extend behavior theory in ways that will help us understand the total organism as it interacts with its environment. The time seems right to attempt a rapprochement between cognitive learning theories and the more traditional, behavioristic approach.

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